Exploring the Impact of Asymmetrical Interfaces on Presence and Group Awareness in Mixed Reality Collaborative Environments

by

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I dedicate this thesis to my family. Without their love and ever-lasting support, nothing of this would have been possible.

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ABSTRACT

Mixed Reality (MR) can be used for mixed presence collaboration by connecting physical and virtual worlds to create an integrated space: remote collaborators connect virtually to a physical workspace inhabited by collocated collaborators. While a "What-You-See-Is-What-I-See" (WYSIWIS) approach holds benefits for group awareness in traditional desktop collaborative systems, WYSIWIS is made problematic by the fundamental asymmetry of many MR configurations. This thesis examines the relationship between interface asymmetry, group awareness, and a sense of co-presence in MR collaborative spaces.

We conducted a user study with three scenarios involving hiding and sharing blended physical-virtual documents around a fused physical-virtual tabletop. The remote collaborator was presented to collocated collaborators as an avatar in a VE in tableside and circumambient display conditions. Collocated collaborators actively sought information about how the physical and virtual environments were mapped chiefly when this was relevant to the tasks, although the circumambient displays generated more curiosity than a single tableside display about how the spaces were connected. Most participants felt that keeping documents away from the tabletop was sufficient to hide them from the remote collaborator, but indications that remote participants could somehow "see" around the physical environment in WYSIWIS fashion led some participants to trust the integrated physical-virtual environment less.

We further investigated how the nature of WYSIWIS abstraction in a collaborative MR environment impacts collaborators' awareness and feeling of co-presence, specifically for tasks involving 3D artefacts. Collocated collaborators used a tabletop display, while remote collaborators used either a tabletop display or a head-mounted display and physical proxy table to work on tasks involving 3D object manipulation. The results of the study suggest that an immersive VE significantly increases group awareness and the feeling of being co-present for both remote and collocated collaborators in comparison to a pure WYSIWIS tabletop configuration. Presenting 3D models in front of the remote participant above the virtual tabletop (Hover) or within the virtual tabletop (Fishtank) did not yield significant differences in group awareness or presence, despite Fishtank providing a more WYSIWIS experience. In addition, a significant percentage of remote participants preferred presentation over the virtual tabletop.

The lack of toolkit support for our research motivated us to combine the software technologies and algorithms used in our work to create a Unity toolkit for rapidly prototyping immersive mixed reality collaborative environments (IMRCE). The IMRCE toolkit helps developers add five components to their systems: hand tracking (visualized and synchronized on all clients), position tracking, touch gestures, virtual reality interaction, and client/server functionality. We evaluated the usability of our toolkit by conducting an A/B comparison between IMRCE and common Unity libraries. The results showed that the IMRCE toolkit made a significant improvement in time to completion, lines of code, number of features, and number of bugs in comparison to development without IMRCE.

LIST OF ABBREVIATIONS USED

MP	Mixed Presence
MR	Mixed Reality
VR	Virtual Reality
VE	Virtual Environment
IMRCE	Immersive Mixed Reality Collaborative Environment
IM	Immersive Mixed Reality
HMD	Head Mounted Display
HCI	Human Computer Interaction
CSCW	Computer-Supported Cooperative Work
WYSIWIS	What You See I what I See
WYSINWIS	What You See Is Not what I See
FoV	Field of View
CoP	Centre of Projection
6DOF	six degrees of freedom
RST	Rotation-Scale-Translation
S-S	Screen-Space
DS3	Depth-Separated Screen-Space
UCL	University College London
MAUI	Multi-User Awareness UI toolkit
WIMP	Windows, Icons, Menus, Pointer

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CHAPTER 1 INTRODUCTION

Remote collaboration can save time, cost, and unnecessary travel. In many cases it is the only feasible option, allowing individuals with critical skills and ideas to work together on a project from multiple locations. Mixed presence collaboration connects groups of collocated and remote collaborators and is beneficial in many circumstances: connecting meeting rooms, connecting a primary school classroom to a distant historical site, or connecting a forensics expert to the scene of a crime, to name a few. Researchers have explored mixed presence collaboration using technologies such as video conferencing [1][2] , display-sharing [3][4], telepresence [5], and virtual worlds [6].

In all cases, problems arise from the fragmented views in mixed presence collaborative environments. Fragmented views arise in situations where collaborators have independent perspectives on a 3D work environment [7], making it challenging to achieve common ground. This is exacerbated when collaborators use different technologies to interact with the shared environment [7]. For example, a person in an immersive virtual environment can easily look at a 3D object from different angles without touching it, but a collaborator using a touch tabletop has a single perspective of a 3D object without rotating the view or the object of interest. These asymmetries can impact mixed presence collaboration: access differences to shared objects might impact coordination, incomplete information about access and permissions can lead to privacy ambiguity, and collaborators may be challenged to understand how their actions are translated into the shared space and manifested for collaborators with different views or interface characteristics. Altogether, these issues may lead to a lack of strong group awareness and create *presence disparity*—a different perception of the presence of other collaborators depending on their physical location and/or interface.

In this thesis, we used two different mixed reality collaborative environments to study the connection between interface asymmetry, group awareness, and a sense of co-presence, and whether such environments can help collaborators increase their awareness and sense of co-presence to keep presence disparity low.

1.1 Context and Motivation

The nature of group work has been the subject of research in different disciplines including management, social psychology, and sociology. Research in social psychology focuses on group processes (how a person works with other group members to complete a task) and decision-making [8]. In sociology, research focuses more on work units and their organizational structure [9], while teamwork and participative management (involving collaborators in the decision making process) are the main areas of focus in management [10]. Most of this research highlights the benefits of cooperation, including increased motivation and productivity. In parallel, computer scientists try to build useful systems for collaboration and also show how information technology can improve teamwork and increase productivity [11].

Mixed presence (MP) collaboration connects workspaces in different physical locations. Each workspace can employ multiple interactive devices including tabletop displays, laptops, tablets and handheld devices [12]. MP collaboration has become more common in some domains, including healthcare, government, education, and sports. Using virtual worlds for MP can promote a sense of co-presence during MP collaborations [13][14][15][16][17].

Technologies for sharing in physical and virtual collaborative environments are being developed and deployed with increasing rapidity, introducing physically–virtually blended spaces into education [18], training [19], work[20][2], and entertainment environments [21][22]. These physically–virtually blended spaces are sometimes called *hybrid spaces* [23][24][25].

Peripheral awareness is one of the benefits of an immersive MP system [26]. It can help collaborators acquire more knowledge about the remote collaborative site; information can be gained about individuals who are joining or leaving the space, the appearance of the room, and the position of collaborators relative to shared space (around tabletops, or in front of large displays).

Olson and Bly [11] explained that designing tools for collaborative environments usually involves three goals:

- To connect remote physical spaces and provide an integrated collaboration space.
- To increase the capacity of reciprocal interdependence through providing a more efficient method to share and access shared information. For example, sharing information on a shared virtual table instead of emailing information to each person.
- To help collaborators' reciprocal interdependence by improving the accessibility of shared information.

However, sharing documents and information between collocated and remote individuals while using different technologies and devices engenders many technical and usability challenges. The problem is further complicated when we consider mixed reality collaborative environments (MRCE). We need to understand how to blend the user experience of different types of devices, and potentially different mediums (real artifacts vs. digital) while interacting and collaborating with others—in ways that still foster a sense of connectedness and shared experience.

This thesis explores a number of important questions related to the shared experience in these types of systems:

- How readily do collaborators around a physical tabletop transfer their physical document privacy behaviours to a mixed presence scenario?
- What are the different types of cues that indicate how physical and virtual environments are linked? How do these cues impact privacy-related actions?
- Does connecting remote collaborators to a collocated team via an immersive environment promote better group awareness in comparison to connecting identical physical-digital workspaces (in particular tabletop displays)?
- Does using a different perspective view of 3D contents and access for manipulation of 3D contents (a 3D projection that mimics the tabletop perspective vs. a 3D projection that optimizes visual exploration and object selection) inside an

immersive environment make a difference in group awareness and presence disparity?

To begin examining these critical issues, we started our research by designing a mixed presence environment that connected a remote collaborator with collocated collaborators through a virtual café to work on linked physical-digital 2D documents. We used this initial design to evaluate privacy and security *strictly within the collocated environment* during the collaboration between collocated and remote collaborators.

The results of the first study showed that collocated collaborators actively seek cues and information about the collaborative environment with the objective of updating their mental models and increasing their context and group awareness to manage their collaborative activities. We identify four types of cues that collocated collaborators use to construct a mental model: responsive cues, environmental cues, event-based cues and communication-based cues.

Awareness and privacy are intertwined concepts [27][28]. Markopoulos et al. [27] explain that there is a 'trade-off and a tension' between privacy and awareness. Lack of awareness can result in collaborators allocating less attention to protecting their privacy. On the other hand, more awareness provides opportunities for collaborators to violate others' privacy. Panoe [27] explains that high privacy restrictions can limit the acquisition of knowledge and awareness, possibly leading to less involvement in collaborative activities. Less involvement in a collaborative activity can lead to more presence disparity effects in remote collaboration scenarios. Our results also confirmed that collaborators are actively looking for cues that increase their knowledge and understanding of the task to be more aware of their privacy actions and handle their collaboration with counterpart collaborators.

Media spaces are settings that allow individuals to work and collaborate together, even when they are not present in the same physical place [29]. Developers were aware of the relationship between privacy and awareness and potential privacy problems of having audio and video on all the time. To address this problem, they tried to provide reciprocity or at least symmetry (collocated and remote see the same information related to each other's) [30], however hardware limitations restricted the amount of symmetry that can be achieved. Many of the media space prototypes tried to maintain privacy while providing awareness information [28] [31] [27].

We continued our investigation of awareness and presence by designing a new mixed presence collaborative environment that allowed us to study both collocated and remote collaborators. We used our new immersive mixed reality collaborative environment (IMRCE) to explore the impact of using an immersive environment and a virtual tabletop on group awareness and presence in comparison to using only a physical tabletop. We also explored the impact of two different fields of view on group awareness and presence while working in an immersive virtual environment.

The results of the second study showed that the remote participant can benefit from the immersive environment for collaboration and work on 3D objects while improving aspects of collaboration such as awareness and presence. We also found that using an immersive virtual environment for manipulating 3D models in collaboration with collocated collaborators helps remote collaborators to increase their group awareness and the feeling of co-presence (keeping presence disparity low). Also, the results indicated that using an immersive virtual environment to provide a relaxed WYSIWIS field of view that allows collaborators to manipulate 3D models will increase group awareness in comparison to using only tabletops.

Finally, we converted our design into an opensource toolkit for rapidly prototyping an immersive mixed reality collaborative environment around mapped virtual-physical interactive displays. Using this toolkit, deemed IMRCE, developers can design systems that allow different combinations of co-presence collaboration. We evaluated the IMRCE toolkit itself in a two-day programming study. The results of the study showed that using IMRCE significantly reduced the time of development and number of coded lines in comparison to when participants worked from API/libraries of their own choice or from the provided list.

Objectives and Contributions

Four goals were pursued in this thesis:

- To explore ways of promoting group awareness of collaborators while
1.1.1 collaborating around mapped virtual-physical tabletops.
- To explore ways of decreasing presence disparity and increasing the engagement and involvement of collaborators while working effectively on shared tasks in a mixed reality collaborative environment.
- To explore privacy mechanisms suitable for physical-virtual blended collaborative environments.
- To provide a toolkit that helps researchers and developers rapidly prototype immersive mixed reality collaborative environments (IMRCE)

The activities culminating in this thesis are the development of a prototyping toolkit for mixed presence collaborative environments (called IMRCE), a study performed to evaluate the IMRCE toolkit, a study exploring digitally-mapped physical privacy mechanisms contributing to the SecSpace [32] framework for usable privacy and security in mixed presence environments, and a study exploring how a heterogeneous configuration of immersive 3D interaction and touch-based 3D interaction impacts awareness and presence disparity in a mixed presence environment (designed with use of IMRCE).

Our research resulted in several findings and deliverables. The results of the second study indicated that integrating VR into MP-MR environments allows developers to implement relaxed WYSIWIS interfaces for manipulating 3D objects. Also, using VR environments provides circumstances that are in a sense a more “natural” and familiar collaboration medium for collaborators who are using head-mounted displays (HMD) to manipulate 3D models. However, results from the first study illustrated that manifesting physical actions in virtual actions and mapping physical documents into digital documents in the virtual world makes managing privacy more challenging, and developers of MR-MP systems need to carefully contemplate mechanisms to increase collaborators' awareness of events and the collaborative environment.

By considering consequential communication concepts in our designs and following Baker et al.'s [42] categorization of consequential communication, we classified cues in MR-MP environment into four types which can be considered during implementation of MR-MP environments: responsive, communication-based, environmental and event-based cues. Implementing cues from these four categories will provide information that can satisfy consequential communication concept. Our IMRCE toolkit supports developers to add cues from all these four categories to their applications.

Our results suggest that the VR environment helped collocated participants to have a stronger connection with remote participants and increase their awareness and having a greater connection to their counterpart collaborators. However, our findings also showed that participants did not pay much attention to the VR environment and were focused on the study activity, suggesting that developers of MR-MP systems should focus on supporting the shared activities.

The IMRCE toolkit is the main deliverable of the thesis work. Our free Unity toolkit allows developers to rapidly prototype heterogeneous MR-MP environment applications. Our toolkit allows researchers to develop touch applications and VR applications with out of box support for implementing the network, hand tracking and position tracking. The IMRCE toolkit helps developers to connect touch displays of different sizes with virtual displays inside an immersive environment.

1.1.2 Organization

The rest of this thesis is organized as follows. Chapter Two summarizes the related work on awareness, presence, privacy and security concepts, and other concepts that are related to our thesis work. In Chapter Three, we review our first study design on usable privacy and security for MR collaborative environments and the results of the study. Chapter Four explains our second study design for exploring group awareness in an IMRCE the results of the second study. In Chapter Six, we describe the IMRCE toolkit, the evaluation method for the toolkit and the result of the evaluation. Finally, Chapter Seven and Eight concludes this thesis with a discussion of our work, a summary of our contributions.

CHAPTER 2 LITERATURE REVIEW

This chapter presents a survey of previous works for this thesis. In the first section, we review concepts related to awareness, presence, presence disparity, model representation and touching and manipulating 3D objects to introduce the concepts that we used in our research. We continue with a review of mixed presence collaborative environments, telepresence systems and mixed presence toolkits in the third and fourth sections respectively. In parts five and six, we provide a brief discussion of metrics and statistical analysis methods.

2.1 Awareness

The concept of awareness has been used widely in Human-Computer Interaction (HCI) and Computer-Supported Cooperative Work (CSCW) research. Christiansen and Maglaughlin [33] classify awareness into four categories:

- Workplace awareness: The knowledge of tasks within the collaborative environment,
- Availability awareness: The knowledge of the availability of people and objects,
- Group awareness: The feeling of being involved in a group and their activities and understand the dynamic of the group, and
- Contextual awareness: The knowledge and contextual information like the location of a user.

Group awareness as defined above is most directly related to presence. However, these categories are not independent, and there is overlap between them. For example, a remote collaborator works with a group of collocated collaborators. The remote person cannot feel involved in the group activity (group awareness) without grasping the ongoing activity (workplace awareness) or distinguishing collaborators that are working in the group activity at the counterpart location (availability awareness).

Dourish and Bly [34] explain awareness as "an understanding of the activities of others, which provides a context for your own [actions]." Dourish's definition of awareness is formed around social interaction and how people maintain awareness of others around them. “Awareness system” is used as a broader term that can be defined as "systems intended to help people construct and maintain awareness of each other’s activities, context or status, even when the participants are not collocated" [27].

Cress et al. and Kimmerle [35] explain group awareness as receiving information about other people, about objects that are shared among group members and about the group process and activities. Adams et al. [36], Robinson [37]; Endsley [38] describes three characteristics of awareness relevant to group work:

- Awareness is knowledge about the state of an environment bounded by time and space [36].
- Awareness needs to be updated and maintained along with environmental changes [36].
- Maintenance of awareness happens through interactions exploring the environment [38].

Awareness is dependent on the availability of timely information about the users' performance and system status to have a high level of awareness and complete control over the task.

Consequential communication refers to a source of information that comes from body language and actions such as hand/head movement, position, posture, voice, and gaze. It plays a vital role in group awareness during collaboration. Consequential communication can intentionally and unintentionally reveal information to others. Gutwin [39] states: “Watching other people work is a primary mechanism for gathering awareness information about what’s going on, who is in the workspace, where they are, and what they are doing.” Removing social context cues such as location, gestures, apparel, and nonverbal behaviour during remote collaboration impacts collaboration and changes the social situation [40]. Sherman explains that removing the sources of social cues (e.g., entering or leaving the room) make collaborators more self-centred and gives them a negative perception of others [41].

Baker et al. [42] divide consequential communication into three categories:

- **Actions coupled with the workspace:** the knowledge that a collaborator can gain by observing other collaborators' actions and behaviours while interacting inside the collaborative environment. For example, the distance between collaborators and a workspace indicates if they can reach the workspace or see the contents of it.
- **Actions coupled with the conversation**: cues that result from conversational partners and help collaborators continuously adjust their verbal behaviours [43].
- **Intentional communication:** specific visual actions and gestures that happen along with verbal communications and can take many forms [42].

Our immersive mixed reality collaborative environment design provided cues from all three categories of consequential communication to help collaborators increase their group awareness. For example, a hand tracking system provided cues that fall in all three categories: the position of hands on the shared object is in the first category, moving hands while talking falls in the second category and using different gestures during talking falls in the third category.

Spatial tasks are intertwined with the spatial knowledge of an environment. Spatial knowledge contains both knowledge of the environment and the spatial knowledge of 3D contents. Therefore, spatial awareness is a necessary element for efficient performance while performing spatial tasks [44][45][46]. The spatial knowledge of the environment was highlighted in our first study. In the second study, the spatial knowledge of the 3D contents was mostly highlighted.

2.2 Presence

We investigated whether using an immersive environment and a virtual tabletop to connect remote collaborators to collocated collaborators (who are working on a physical tabletop) has any impact on group awareness in comparison to manipulating information on a physical tabletop at both remote and collocated locations. Also, we studied whether using a different perspective view of 3D contents and the type of access the VR users have for manipulation of 3D contents inside an immersive environment makes a difference in group awareness and presence disparity. In the next two subsections, we examine the two concepts of awareness and presence disparity.

Witmer and Singer [47] explain the immersion in an immersive environment as "a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences" [47], and involvement as "a psychological state experienced as a consequence of focusing one's energy and attention on a coherent set of stimuli or meaningfully related activities and events." Witmer and Singer [47] discussed that the feeling of presence is the result of having both immersion and involvement. Schubert et al. [48] argued that a virtual environment (VE) is perceived and interpreted by combining possible patterns of actions (each action has an impact on the environment and creates stimuli). In other words, that presence in a virtual environment is tied to the actions that we consider possible in the virtual environment. As Zahorik and Jenison [49] put it, "presence is tied to action in the environment."

Schubert [48] argued that there are two connected factors involved in the emergence of presence: construction of a mental model and attention allocation. Schubert continued, explaining that to have a conscious presence experience a person should be aware of possible action patterns and the attention allocation (how much attention a person gives to an action or an object).

A VE can provide cues to its user to gain information related to action and attention (for example, seeing the other collaborator's hand gestures and position, or the location of other collaborators mapped to the VE). This applies more when the collaboration happens in an MR environment. Each person should be aware of the status of the group such as who is talking, who is working on a specific document, what the current discussion is about and what their responsibility is.

2.2.1 Presence Disparity

Tang et al. [50] identified display disparity and presence disparity as two issues to consider when designing MP environments. Display disparity is the issue of how collaborators around heterogeneous displays (e.g. tabletop, wall display) orient their work on the same documents. For example, collaborators around the wall display have a different perspective view of collaborators around the tabletop. Presence disparity is one of the core problems in a mixed presence collaborative environment [50]. Collocated collaborators tend to focus on the other collocated collaborators, and they pay less attention to the remote collaborators. Therefore, they tend to collaborate more with people around them [50], and it can lead to the conversational disparity. Being collocated dominates collaborative activities due to the effectiveness of face-to-face interaction. As a result, collaborators direct most of their attention to collocated collaborators [50].

2.2.2 Mental Map and Presence

An individual's mental representation of an environment is known as a spatial mental model. Spatial mental models are map-like mental constructs that are gradually built and updated by inspection and acquiring elements of the world [51]. Rouse defines a system mental model as "... the mechanisms whereby humans can generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states" [52]. In MR/hybrid spaces the spatial mental model and the user's model of the system are closely intertwined; therefore, individuals build a mental model that contains both spatial and system elements.

Dix [53] identify three type of spaces in an mixed reality (MR) system and their impacts on the cognitive process of mapping on them: the physical environment, positioning relative to physical and virtual space, and the virtual environment. We extend Dix's model to MR-MP environments. Imagine having an MR-MP system that connects remote collaborators through a virtual model of their collocated collaborators' physical environment. Collocated collaborators build a mental model of the physical environment, and remote collaborators build a mental model of the virtual environment. Both types of users can mentally inspect their mental model and identify different locations, but when collocated and remote collaborators connect to each other they need to update their mental models in a way that maps the aspects of both physical and VEs.

Reilly et al. [54] demonstrate that the physical and virtual elements of an MP collaborative environment, including its contents and different interface cues, all influence how people build their mental model and ultimately how they collaborate. A correct mental model can increase the user's contextual and group awareness and help collaborators to manage their sharing and collaboration activity with more security and privacy by using the knowledge they acquire while building their mental model.

2.3 Privacy and Security

Collaboration in a collocated environment requires different privacy actions such as managing the visibility of documents or sharing with specific people. For example, during a meeting, a participant may wish to share his documents with some of the attendees in the room but hide it from others. Also, a small subgroup may want to have a privacy related to its position and relation to the other participants. Being aware of the presence and locations of people in the collaborative environment is necessary and helpful for individuals to handle their privacy more effectively. For example, a group of doctors have a meeting to discuss a patient's condition, where nurses or staff may walk in or out. Being aware of other people's presence in the room reduces the chance of exposing the information to unauthorized persons unintentionally.

Cultural differences, background knowledge, levels of technical skill and experience in working with collaboration devices impact a users' behaviour in managing their privacy and security. Also, different organizations have their own privacy and security rules especially when they are dealing with a large amount of sensitive data. Considering different privacy rules when collaboration occurs between different organizations can create certain ambiguities that need to be addressed. For example, a company may permit its employees to have access to certain documents while another company does not give such access to its employees. Alternatively, for instance, one company lets its employees bring their digital devices such as smartphones, tablets and laptops to meetings and use them to take notes or images. However, another company does not let its employees bring their own digital devices to meetings and restrict them to using digital devices that are provided by the company. These considerations make collaboration between companies with different security and privacy mechanisms a challenge.

Privacy and security mechanisms usually focus on defining specific rules and actions for the users, and encouraging and assisting collaborators to follow the rules to protect their privacy [55][56]. According to Bødker [57] and McCarthy and Wright [58], reflecting the users' experience in using technologies and collaborative environments is necessary to have the best results in designing user-centric ICT tools. Therefore, relying only on defined rules such as keeping a specific distance from other participants or holding documents in a certain way, are not enough and the best solution for privacy in user.

We used an exploratory approach to finding physical patterns of security and privacy actions to use in designing heterogeneous, document-centric, mixed presence collaboration; at the same time, we were interested in learning more about the natural behaviours and mechanisms that people use to protect their privacy and security during collaboration in both digital and physical worlds.

2.3.1 Privacy and Security for Collocated Collaborators

Here we look at some of the privacy and security approaches to the collocated collaborative environments. UbiTable [59] gives three levels of security access to the participants for sharing information:

- Private: at this level, no one can have access to the documents, and only the owner can decide to delete or modify the information.
- Personal: information in this level is seen as semi-private, for example, when collaborators stand around a tabletop; a personal space will be attached to them on the tabletop close to the place are standing. They can keep their documents in this space, and nobody can have access to them digitally, but if they decide to share a document, that particular document becomes public and accessible to everybody in the collaborative environment.
- Public: all participants have an equal level of access to public documents, and they are visible to everybody.

Semi-Public Display [60] focuses on the applications of public displays used by small collocated groups. Collocated collaborators in small groups usually have a high level of awareness about each other. A Semi-Public Display divides a display into multiple spaces for different purposes, for example, a space for reminders and notification, and another space for collaboration. Semi-Public Display, presents group activities over time, using a graphical representation. The system attempts to protect the privacy of members by using abstract visualizations and icons.

Virtual walls [61] is a good example of self-defined privacy and security rules. Collaborators in this system have a chance to control their digital footprints by defining rules on the visibility of data in different regions of the physical space.

SharedTable [60] is an example of privacy and security concerns in new collaborative environments. SharedTable is designed for communication between separated parents and children. This system benefits from having video chat, shared tabletop space, drawing and learning tools. However, there is no mechanism for handling privacy while people are around, and collaboration is going on. Authors suggested using the system inside a child's room and in the specific time, but this is not a generalizable solution to limit people to specific time and location for using a system. There are some guidelines for managing privacy in media spaces [38], but handling the privacy in a mixed presence environment, is a challenging problem and needs more research.

2.3.2 Privacy and Security in Collaborative Environments

People utilize their prior experiences and the strategies and practices already developed through these prior experiences to make sense of encounters with IT artifacts [58]. Therefore, we are exploring how prior experiences with collocated collaboration influence how people choose to share documents with collaborators in mixed presence contexts. There is a novelty in this approach since often solutions do not build on prior experience: instead, they focus on establishing secure procedures that users should follow, specify proper security policies, and provide end-user assistance with these procedures or specifications [55][56].

Inconspicuous privacy actions provide an opportunity to avoid conflicts and confusion between collaborators. However, sometimes a privacy action needs to be communicated to collaborators, as when revealing a card in a card game. Physical privacy actions can involve both conspicuous and inconspicuous elements: to continue with the card game example, holding cards close to one's chest is conspicuous, while slightly adjusting their orientation to allow a friend to see them may be inconspicuous.

In mixed reality configurations, we want to map privacy actions across linked physical and virtual spaces. This challenge one's ability to achieve conspicuous and inconspicuous privacy actions, due to incongruities in the experience of local and remote players. For example, physical cards may be tracked, and their horizontal orientation mapped to their visibility in a linked virtual world. If this mapping is discrete (i.e. either visible or not visible), then inconspicuous privacy may be compromised, as the actor needs to be wary of the card orientation threshold lest they unintentionally reveal their cards. A discrete mapping also gives remote players a disadvantageous view of the other players–leaving only conspicuous privacy actions visible—they would be unable to observe how players sort their cards, for example. If the mapping is continuous, for example by positioning cards in the virtual 3-D space according to their orientation in physical space, players at the physical game table might not know what remote players can and cannot see, again making it difficult to have control over how conspicuous or inconspicuous their actions are. With a continuous mapping, remote players may be at an advantage, given a real-time 3-D view of how cards are held at the physical table while being able to control exactly when their cards become visible.

2.4 Model representation

In the first study, collocated collaborators were immersed in a circumambient virtual reality environment while they were standing around the mapped physically-virtually tabletop.The collocated collaborators were told that the remote collaborator uses the same virtual environment and he/she is working on the virtual tabletop. Collocated collaborators thought that they had the same field of view as the remote collaborator. Note that the remote collaborator was one of our researchers. In the second study the remote collaborators worked around a virtual tabletop to perform a series of 3D manipulation tasks directly within the virtual tabletop. The field of view around the virtual tabletop is similar to the field of view that collocated collaborators have. In another condition, the remote collaborator saw the 3D models hovering over the virtual tabletop. In this section, we briefly look at the concept of multiple viewpoints and some of the research that has been done in this area.

There are two primary methods of representing shared data for collaborators in a collaborative environment. WYSIWIS (What You See Is What I See) interfaces [62] provide the same field of view (FoV) for all collaboration. WYSINWIS (What You See Is Not What I See) interfaces [63] provide multiple fields of view (FoV), and each collaborator can use a different view of the environment or shared objects.

Strict WYSIWIS provides the exact image view for all collaborators and relaxed WYSIWIS allow for looser constraints around display space, time of display, subgroup population, and congruence of view [62]. Strict WYSIWIS are simply too inflexible to use for a collaborative environment [3][4]. WYSINWIS applications are useful when collaborators require different input and output [65].

Snowdon [63] used the concept of multiple perspective views to introduce subjective virtual environments. A subjective virtual environment allows users to choose a perspective that suits their needs better. For example, consider a group of material engineers working with mechanical engineers to design a new engine. A material engineer can look at the model in term of material stress and strain while a mechanical engineer can see the model in term of strength and connections.

CALVIN [66] is a method similar to the subjective view that uses a notation of Mortals and Deities. Mortals are collaborators that can see and manipulate the shared models from an egocentric perspective. Deities are collaborators that can view and modify the model from and exocentric perspective. Several studies have discussed the potential of multiple perspectives to enhance learning by allowing collaborators to change their views to satisfy their particular needs during collaboration [67][68][69][7]. However, using multiple perspectives can cause difficulties in discussing and coordinating group activities since collaborators have different views [70][71]. To give an example, imagine a team of designers working on an airplane model. Two collaborators work on the right wing while standing around a physical tabletop. The chief designer uses an HMD and immersive VE. The chief designer can tilt his head and walk around the model without touching the model while engineers need to rotate the plane to see the other side of the aircraft. The chief designer walks around the model and requests a change on the left wing in the design. However, the individuals working on the right wing are not able to address this change because they are using an alternate view that differs from the chief designer.

Park et al. [7] explored the concept of using multiple perspectives for collaborators through an exploratory study with a focus on scientific visualization. Three pairs of participants were recruited. Each person used a cave visualization tool to collaborate with others. An avatar represented each person with long pointing rays spreading out from their hands to point to a particular location on the 3D model. Park et al. defined three conditions for this study. In the first condition, collaborators were only allowed to use a localized (private) view. In the second condition, they could use a global (fully shared) view, and in the last condition, they could choose between the local and global view. To complete the tasks, participants had to use data visualization and talk with their partners. The results indicated that collaborators worked most of the time independently, and they were less willing to collaborate even with a shared global view. Park explains that their study did not efficiently explore the benefits of using multiple perspective views.

Provenzano et al. [72] studied the independent positioning and manipulation of multiple shared objects with remote viewpoint awareness in a 3D collaboration desktop. Provenzano suggested two viewpoint metaphors: the remote user's viewpoint and local viewpoint. The remote user's viewpoint provides a sense of the location of other collaborators' viewpoints related to the shared object. A local viewpoint allows collaborators to have the remote user's view of the shared objects. Groups of 2-5 participants worked together from remote locations. Collaborators had to switch between personal and group activities while they were collaborating. Participants were asked to use a virtual camera to take eight pictures of a virtual person that was skiing. Participants had to work together on tasks such as setting the speed, view angles, and zoom. The results of the study confirm their hypothesis namely that the “local” viewpoint is more effective and useful than the “global” viewpoint for collaborative manipulation activity [72]. To explain their findings, Provenzano et al. discuss why collaborators need to share views instead of giving a rough idea of what a remote collaborator’s point of view is during a collaborative activity that involves physical manipulation of an object. This will help collaborators have an idea of what the other collaborators are looking at. This also helps collaborators to increase their awareness and feeling of being co-present and to better manage their privacy.

2.4.1 Perspective vs. Parallel Projection

Hancock et al. [73] investigated the impact of different projections on people’s judgment of object orientation during collaboration around a tabletop. Usually, 3D projections on tabletops have one virtual viewpoint. As a result, collaborators situated at different locations around the table can see a distorted view of some of the 3D objects. There are two primary projection geometries: perspective and parallel. If we use straight lines (rays) to represent the view of an object, then in perspective view rays go from every point of the object to a centre of projection (CoP) and in parallel view rays are parallel in a fixed direction. In perspective projection, a collaborator will have a geometrically correct view of the object if their point of view (PoV) is coincident with the CoP. However, in parallel view, collaborators can have a geometrically correct view of the object from different PoVs.

Perspective projection provides a more realistic view of the object, which is closer to the human visual system. In the perspective view, the size of the projected object has an inverse relation with the distance of the object from CoP. Also, angles and parallel lines are not preserved. In parallel projection, objects are less realistic, and parallel lines are preserved therefore it is easier to use a lateral view for measurement. Using parallel projection in architecture and engineering is common due to preserving the parallel lines. However, a parallel projection cannot generate a geometrically accurate retinal image to make the same impression on the viewer’s retina that is equivalent to what a real scene can generate in their eyes [73]. Hancock et al. ran a study with twenty-four participants. The main result of the study shows that increasing discrepancy between the location of CoP and PoV results in increasing the error in people's ability to judge the correct orientation of 3D objects.

2.5 Touching and Manipulating 3D Models

Many studies have been done on collaboration and awareness in MP collaborative environments. Most of this research focused on working on 2D shared documents because a wide range of collaborative activities falls into this category. However, collaborations involving 3D objects are less explored. The use of 3D software and models is increasing rapidly within a broad range of professions such as architecture, engineering, art, mechanical engineering, game development and fashion design. It is, therefore, necessary to have more research on using 3D objects in MP collaborative environments. Also, we used an HMD to provide an immersive environment for remote collaborators and give them the sense of co-presence. Using 3D manipulation let us strengthen the remote collaborator's engagement through using the capacity of an immersive environment in presenting 3D objects.

2.5.1 Manipulation Controls for 3D Models on Touch displays

Garner [74] in his theory of the perceptual structure of visual information explains that a multi-dimensional object has an integral and separable structure. "Visual information has an integral structure if its attributes can be perceptually combined to form a unitary whole. If visual object attributes show perceptually distinct and identifiable dimensions, they are separable." [75] According to Garner's theory and definition of integral structure, 3D manipulation tasks are integral tasks because orientation and the position of a 3D object are two integral attributes. Ingram et al. [76] show that human fingers have separable DOF. The mismatch between the nature of 3D manipulation as integral tasks and human fingers with separable DOF makes it challenging to inscribe the correct mapping between the two structures while working with multi-touch displays [77].

Hancock et al. [78] introduced an interaction paradigm that has the benefits of force-based interaction complete with full six degrees of freedom (6DOF) manipulation (called Sticky tools). “Sticky tools” allows users to use one finger to move objects, two fingers for lifting an object in the Z direction and rotating it around Z, three fingers to rotate an object in the direction of the Y and X-axes.

Reisman et al. [79] highlight the fact that Rotation-Scale-Translation (RST) is the de facto standard technique for 2D object manipulation on a touchscreen, and it can be extended to 3D object manipulation. They presented screen-space (S-S) a method for capturing the semantics of the traditional 2D, RST touch interaction and extend them to 3D interaction. S-S needs at least three fingers in contact with an object for providing 6DOF. However, the authors also did not perform a formal evaluation for S-S.

Martinet et al. [80] introduced the Depth-Separated Screen-Space (DS3) technique for 6DOF manipulation. DS3 separates translation from the rotation. The control is achieved by analyzing the direction of fingers on the object. Authors discussed that integrating 6DOF was less efficient than having independent rotation and translation. Their study confirmed that integration of both translation and rotation decrease performance, coordination, and user satisfaction [80].

Liu et al. c presented a technique for full 6DOF that uses only two contact fingers. Liu et al. evaluated their technique with ten participants. Their results showed that the two fingers technique performed better than Screen-Space and DS3 methods. However, the authors mentioned that their technique might not be a suitable for precise manipulation of a 3D
2.6 object.

Mixed Presence Collaborative Environments

VideoArms [81], Media Spaces [26], Almost Touching [82], WaaZam! [83], Clearboard [84] and Carpeno [6] are examples of research projects using shared space environments to permit remote collaboration. However, these systems require that all the participants have the required symmetric hardware and software to collaborate. While having identical interfaces can make it more straightforward to see and interpret the actions of a collaborator, this also limits the flexibility of the collaboration and can be financially costly for users.

Media Spaces [26] are video-based MP collaborative environments intended to support both technical (necessary infrastructure) and social aspects of collaboration. Media Spaces is one of the first MP collaborative systems that bring social events and activities together across time and space [26]. ShareTable [82] uses video chat and a shared tabletop task space. It was successful in providing "metaphorical touch" and a sense of closeness and co-presence. ShareTable was evaluated as a tool for connecting kids to their parents in divorced families. WaaZam! [83] is a video communication system designed to support creative play in customized digital environments located in different geographical locations. It allows remote collaborators to use the same virtual space with support for object play, body merging, transformation, and gestural interaction. The results of a user study indicated that personalization allows collaborators to modify the environment based on their needs. Moreover, it increases the richness and depth of the activities. Also, being in the same virtual space with other collaborators increases engagement during the collaboration.

Lighthouse [85] was an MP application that allowed the web, virtual and physical visitors to a museum to share their visit with each other. This research provided one example of how an MP collaborative environment can support social experiences and interaction from remote locations.

Pinho et al. [86] describe a framework for the development of cooperative manipulation techniques. "Cooperative manipulation refers to the simultaneous manipulation of a virtual object by multiple users in an immersive virtual environment" [86]. Pinho et al. evaluated their collaborative techniques in a user study with six pairs of participants. Both users wore an HMD, and one hand and their head were tracked with a Polhemus Fastrak tracking system. Participants were asked to work together to complete one of three tasks: place a set of objects on a platform, move a couch through a door or place set of objects between some walls [86]. Their preliminary results show that cooperative techniques increase performance and usability in complicated manipulation scenarios (relative to simple scenarios), especially in situations where a single user cannot have some of the degrees of freedom (DOF).

In an MP, collaborators could be collocated or remote, with fragmented views and perspectives of others' spaces. Also, the virtual environment can give the ability to virtual collaborators to produce virtual gestures and use their virtual embodiments during collaboration. Hindmarsh et al. [87] conducted an exploratory study of object-focused collaboration in a desktop virtual environment with a focus on fragmented interactions and understanding others' perspectives. They identified four fundamental limitations that need to be addressed for achieving better support for distributed collaboration: limited horizontal field of view, lack of information on different actions, slow movements due to network latency or graphics processing and disallowing collaborators to perform a combination of actions concurrently. However, latency and graphics processing problems are less of an issue these days due to a significant increase in internet speed and graphics processing abilities.

Mortensen at al. [88] ran an observational study on remote collaboration in a shared virtual environment. Collaborators at two remote locations negotiated with each other to carry an object together for a few meters. Mortensen investigated the extent to which collaborators in two remote locations can collaborate through a virtual environment. They recruited seventeen participants at University College London (UCL) to work with a pair at the University of North Carolina (UNC). Collaborators at UNC entered the virtual environment using an HMD, and their peers entered a cave that used four projectors to present the virtual environment on the walls of the cave. Collaborators had to negotiate lifting and carrying a stretcher. The data analysis of the questionnaires indicates that co-presence and task performance are significantly and positively correlated with each other.

2.7 AR/VR Telepresence Systems

Holoportation [89] is a system that provides MR telepresence. Holoportation uses a depth camera for real-time 3D reconstructions of an entire space, including people, furniture and objects, allowing remote collaborators to see each other in space and work with each other. The system was evaluated in a study with 10 participants. The results of the qualitative analysis showed that participants developed a strong sense of interpersonal space awareness. They also quickly adapted to the mixed reality setup for collaboration, and they had a more natural interaction during their collaboration in comparison to video conversation.

Room2Room [90] is another telepresence system that uses projected augmented reality for co-present collaboration between two remote collaborators. Room2Room uses a Kinect camera to scan one physical location. After 3D reconstruction, the capture location will be projected in the other location. Pejsa et al. [90] used an assembly task to evaluate their study. One participant played the role of an instructor and the other participant played the role of an assembler. The assembler was supposed to assemble permuted-blocks by following the instructor's instructions. The results of the evaluation showed that Room2Room increased the sense of co-presence and decreased the time of completion of the assembly task in comparison to the use of Skype for collaboration.

Maimone and Fuchs [91] introduced a proof of concept telepresence system that captures and reconstructs a 3D environment in Realtime using depth cameras. Their system also uses an eye tracking system using depth sensors. This prototype was not evaluated formally. However, the authors provided a technical analysis of the system, their technical study found positive eye detection on >99% of frames.

Immersive Group-to-Group [92] is a telepresence system that allows distributed groups of users to meet in a shared virtual 3D world. This system allows collaborators to use pointing gestures during collaboration. Beck et al. [92] evaluated their system with 12 participants (four groups of three). A researcher connected remotely with participants using the Group-to-Group system. Collocated and remote participants used pointing gestures to point to the 3D model of a series of buildings in a virtual city and discuss them. The results of the study showed that pointing provides an opportunity for collocated and remote collaborators to directly communicate.

MirageTable [93] is a telepresence system that used a depth camera, a stereoscopic projector, and a curved screen to provide an augmented shared space between collaborators and allow collaborator to see each others. Benko et al. [93] performed a study on 3D perception and the image quality of their system. The results show that participates has low average error in depth estimation using MirageTable and they were able to perceive 3D shape over a curved geometry background.

Despite being promising prototypes, the work discussed so far did not lead to the development of toolkits to facilitate development of similar systems. The systems outlined require expensive hardware and/or extensive setup, making them less feasible for *ad hoc* mixed presence collaboration. The next section describes research efforts to create toolkits for mixed presence.

2.8 Collaborative Toolkits

TwinSpace [54] is an MP toolkit which is designed to combine interactive workspaces and collaborative virtual worlds and provides a flexible mapping between virtual and physical space to support efficient collaboration. SecSpace [32] is a software toolkit for supporting usable privacy and security research in MP environments by facilitating the transfer of privacy behaviours between physical and virtual connected environments. SecSpace is an extension of TwinSpace toolkit. The SecSpace toolkit has not been evaluated in a formal study. The Multi-User Awareness UI toolkit (MAUI) [94] is a java toolkit that was designed for collecting, allocating, and visualizing group awareness information. MAUI has been tested within the lab that designed the toolkit in various projects. Their usability analysis showed that the toolkit significantly reduced the time to implement a MP environment. CAVERNsoft G2 [95] is a toolkit for developing collaborative MP applications. This toolkit focused mostly on high-performance computing and data intensive systems in the shared collaborative, immersive environment. MAUI and CAVERNsoft G2 do not support position tracking, hand tracking or touch gestures.

SoD-Toolkit [96] allows developers to use software libraries and “plug-and-play” popular hardware such as Leap motion sensors and the Kinect camera for prototyping MP environment. SoD-Toolkit assumes network and device management and the complicated procedure of connecting different APIs to each other. The toolkit has not been evaluated in a formal study.

PyMT [97] is a toolkit that addresses the challenge of designing multi-touch and tabletop input, WIMP paradigm (Windows, Icons, Menus, Pointer) user interfaces. PyMT provides a different multi-touch widget to allow developers to rapidly prototype a touch application for touch tabletops.

Hand tracking algorithms and representations have been developed and studied before. VideoArms [81],VideoDraw [98], VideoWhiteboard [99], TeamWorkstation [100], KinectArms [101] and ClearBoard [102] are some examples of toolkits and systems that use hand tracking technology. Current methods and algorithms support local hand tracking and visualization as 2D or 3D models. Some of these toolkits/systems allow visualization of a 2D model of hands at the remote location. However, this operates with the use of video capture and is akin to video display sharing. This technique will be impractical in instances in which one of the collaborators works in an immersive virtual environment since the collaborators have a 3D view of models.

KinectArm is a recent toolkit that captures and displays arm embodiments and tabletop gestures on distributed tabletop groupware by using a depth camera. The authors performed an analytical evaluation to evaluate different aspects of the toolkit such as performance, the complexity of using the application and its extensibility. The results of the evaluation showed that the KinectArm toolkit provided a powerful but easy-to-use solution for handling remote gestures on distributed tabletop groupware.

2.9 A Short review of Applicable Research Methodologies

Mixed presence collaboration and the concept of presence are intertwined together. This makes the evaluation of mixed presence environments a challenging process. “The sense of being there” is the most ubiquitous component of the concept of presence and it is depicted through displays, HMD, speakers and other cues [103][104][105]. Slater [103] explains that presence in a virtual environment cannot be established using post-experience presence questionnaires only. Questionnaires are useful in situations where judgments can be made based on a significant amount of prior experience. Questionnaires are also helpful when it is possible to make a comparison between a specific behavioural outcome like voting in favour or against a certain product or action, or cooperating with other collaborators to put different parts of a 3D shared model together to build the final model [103]. Slater believes almost all existing reported presence data is from questionnaires, and there is no independently verifiable information to help us evaluate the presence or to say "this indicates presence" [103]. Researchers might argue that correlating presence with task performance is a solution. However, Slater and Wilbur [106] argued that a logical connection between presence and task performance does not exist, and task performance is the direct result of the user interface, not presence.

Schloerb [107] suggested a psychometric approach (psychometric refers to the technique of psychological measurements such as measurement of knowledge, abilities, and personality traits) to evaluate presence. Schloerb's approach uses noticeable differences between the virtual and physical world. Therefore, it is suitable for software that aims to provide real-world experiences, such as driving and flight simulators. There have been attempts to use collaborators' social actions to measure presence [108]. For example, waving hands or nodding in response to others, or swaying in response to a moving object.

Using physiological measures is another solution for evaluating presence in VEs [109]. Slater [103] argues that physiological measurement is only useful when physiological responses are apparent (ex. response to tense situations). However, physiological responses in a situation where a collaborator is standing around a tabletop listing to others can be different from face to face, and the responses are sometimes unexpected.

Roleplaying is a study method used to help participants feel engaged [110][111]. Also, realistic tasks have the potential to motivate participants to value their privacy and protect their data (even when data is fabricated) [112].

Questionnaires are often used to assess awareness, for example, whether or not specific UI events were noticed [113][114], and more specifically mutual awareness during collaboration [115][116]. Questionnaires are also used to measure co-presence in virtual environments [117]. Slater and Usoh [118] proposed the first questionnaire for evaluating presence and later Slater and Wilbur [106] refined the questionnaire. The questionnaires usually adopt an ordinal Likert scale that is anchored at two extremes, and it has shown to be productive and meaningful in many cases [119]. However, as discussed, there are also criticisms of using questionnaires to measure presence. Freeman et al. [120] argued that the result of questionnaires is unstable in some cases because prior knowledge could impact the results. Alternatively, the results may not discriminate between presence in the virtual environment and physical presence [121].

Interactions between collocated collaborators are mostly unmediated because they are happening directly without intervening technologies. Analyzing unmediated interactions requires an examination of various synchronous activities such as verbal/nonverbal communication and body language. This analysis can result in identifying how humans perform a sequence of social activities and norms [119][122][123]. Jordan and Henderson [122] define interaction analysis as a mixed practice of interactions between each other and with objects. The most common way to analyze unmediated collocated communication has been done through manual transcription, reviewing audio/coded video data and looking at detailed qualitative observations and nonverbal cues [124].

Some researchers have used a tracking system and sensors to detect quantitative data to describe collocated interactions [125][126][127]. Data to be logged during collaboration include full or partial body movements (body motion capture) [128], "oculesic behavior" (eye tracking) [129], vocal signals (via microphone) [130], and physiological responses such as heart rate [109] and galvanic skin response [131].

Video recording and analysis are still the primary method of data capture for participants' behaviours and actions and provide qualitative data. However, due to the limited field of view and angles of a camera and its static position in comparison to dynamic and spatial nature of humans, it fails to collect nonverbal communication and interactions in a quantitative manner [122]. Using multiple cameras can mitigate the problem of the static position of the camera and its limited field of view.

Huang et al. [132] conducted a field study for using large displays during NASA Mars Exploration Rover program. Huang et al. present suggestions for the evaluation of collaborative environments that involve large interactive displays. She explains that the change and evaluation of a task (especially exploratory tasks) over time can impact the way we are using a collaborative environment. For example, during the NASA Mars Exploration Rover program, the nature of tasks became less interactive, and that changed the style of the workgroup. A collaborative system with the ability to support a wide range of activities can help collaborators be creative and change their method of the evolution of a task.

2.9.1 Presence and Awareness Analysis Methods

Benford and Fahlén [133] introduced a collaborative awareness model that can be mapped to special spaces such as an immersive 3D environment. Markopoulos et al. [27] described the six components of the Benford model in their book. **Aura** determines the boundary of interaction between a person or an object. For example, a person that is not around a virtual tabletop cannot interact with other collaborators. The **Focus** is a person's area of attention, for example, the area a collaborator can see is part of their visual focus. **Nimbus** describes to what extent information can have an impact on an environment. For example, one's visual nimbus only extends to virtual walls. **Awareness** is a function of Nimbus and focus. If a person is within an object's nimbus then they can be partially aware of it; if the object is also within the focus of the person, then they can be fully aware of it. **Medium** defines the exact relation between focus, nimbus and awareness. For example, a person wearing an HMD who can see the virtual replica of the remote location is more aware of activities, while when they use voice communication, they are partially aware of actions. **Adaptors** are modifiers on focus and nimbus. For example, position and hand tracking sensors can increase the nimbus.

Markopoulos et al. [27] explain that Gutwin and Greenberg believe that workspace awareness consists of three parts: the type of information, which shapes the awareness; the mechanism collaborators use to gather information, and the way collaborators use the information during the collaboration. To measure awareness, Gutwin relied on five questions: who, what, where, when and how. They used questions stemming from these five categories to analyze awareness in shared workspaces.

Hornecker [134] described the ability of collaborators to work with shared objects and manipulate them as one of the characteristics of an interactive, collaborative environment. Pinell and Gutwin [135] described collaboration as communication and coordination which involves access to shared data and artifacts.

VR is compatible with interpersonal communication if a person can encounter others “in a virtual environment, and effectively negotiate a relationship through an interdependent, multichannel exchange of behaviours” [136]. Ha et al. [137] study the effect of awareness by looking at collaborators’ virtual interpersonal interactions using a tabletop and a virtual environment. They investigated the impact of using different input devices on collaboration and the awareness of both intention and actions. Idrus et al. [138] discussed that input device could have an impact on users’ awareness and interaction [138]. Kainulainen et al. [139] explain that to provide awareness, the system should provide information about the collaboration space and the position of each collaborator.

Table 1 Elements of group awareness (reproduced from [39])

Category	Element	Specific questions
Who	Presence	Is anyone in the workspace?
	Identity	Who is participating? Who is that?
	Authorship	Who is doing that?
What	Action	What are they doing?
	Intention	What goal is that action part of?
	Artifact	What object are they working on?
Where	Location	Where are they working?
	Gaze	Where are they looking?
	View	Where can they see?
	Reach	Where can they reach?

Table 1 shows the elements and questions that Gutwin et al. [39] regard as fundamental for awareness.

CHAPTER 3 USABLE PRIVACY AND SECURITY FOR MIXED REALITY COLLABORATIVE ENVIRONMENTS

Collaboration in a mixed presence (MP) system requires a variety of privacy-related behaviours such as managing the visibility of documents or sharing with specific collaborators. For example, during a meeting, a participant may share documents with selected attendees by carefully positioning and orienting both themselves and the documents. Similarly, a small subgroup may maintain privacy by managing their physical proximity to other participants. Being aware of the presence and locations of people in the collaborative environment helps individuals manage privacy in MP configurations and reduces the chance of exposing information to unauthorized persons unintentionally.

Privacy is a broad term, and it has specific technical meanings in different areas such as social theory and ethics, and also can invoke strong, emotional connotations in daily experience [140]. Here we use a simple definition of privacy that is more in the spectrum of social activities: “the ability of an individual to control the terms under which their personal information is acquired and used” [141]. Security, like privacy, involves user data and its use. However, security also investigates others’ (collaborators and strangers) use of data and the system itself. For example, how the system and its interface is used, designed, and developed [140]. MR-MP approaches, in particular, can face challenges in privacy and security due to the need to manage privacy simultaneously in both physical and virtual space. Depending on the level of integration between physical and virtual spaces, this might include how to manifest physical privacy actions (keeping a document folder closed, for example) in the virtual world, and how to manifest virtual privacy actions (revealing a document on a virtual display, for example) in the physical environment.

In this chapter, we describe the first mixed presence environment we designed and the user study we ran to evaluate privacy and security during collaboration in a mixed presence environment. At the end of this chapter, we present the results of the study.

3.1 Research Questions

In our study, we explored the relationship between physical document-centric privacy and mixed presence collaboration. Specifically, we explored whether the methods that people regularly use for handling privacy and security in physical collaborative environments can ground the designs of privacy mechanisms for mixed presence collaboration. These include simple yet effective physical actions such as tilting a phone to hide the screen from other people and positioning oneself at a distance from others. The two research questions we explored are as follows:

- How readily do collaborators transfer their physical document privacy behaviours to a mixed presence scenario?
- What are the different types of cues that indicate how physical and virtual environments are linked? How do these cues impact privacy-related actions?

We explored this issue through the design and evaluation of three privacy approaches that govern the sharing of paper documents between collocated and remote collaborators simultaneously. The first approach allowed collaborators to share a document with all the collaborators but hide it from strangers. In the second approach, a collaborator shared a document with a chosen subset of collaborators only, and the last approach facilitated sharing just a portion of a document with collaborators. We manifested these approaches in three collaborative activities: a card game, a guessing game, and a bill sharing activity, respectively.

3.2 Environment Setup

3.2.1 Virtual Environment

We decided to use a virtual café scenario as the public space for the collocated and remote collaborators to meet virtually. Participants were told that the remote collaborator (a research confederate) was participating from another city and connected via this virtual café, which was being used as a collaborative distributed workspace by labs in several universities to perform different activities such as working on shared documents, brainstorming and presenting work. During the experiment, avatars could be seen walking around the virtual café, occasionally opening documents, and speaking with each other (the research pre-recorded most of this and replayed during each experiment run, although the remote collaborator and another "interrupter" was live). By doing this, we hoped to infuse the feeling of being connected to a public place and so encourage participants to be more aware of the virtual environment and consider potential privacy implications.

3.2.1 Physical Environment

The study was conducted in a lab space approximately $6m^2$ in size. We used a bottom-projected 70" tabletop display as the document sharing interface. Participants stood around the tabletop during the study. On one side of the tabletop, a 62" wall display presented the location of the remote collaborator in the virtual world; the effect was as though the remote collaborator was present at one side of the physical table in the cafe. Projectors were used to show the virtual café on walls approximately 2.5m from each of the remaining three sides of the table; each projection was >100" diagonal. Figure 1 shows an abstracted sketch of the setup wherein each projector displays one side of the café on the wall of the physical room.

We used four cameras during the study. Camera 1 was used to record the study, camera 2 provided a live stream to the remote collaborator, camera 3 tracked fiducials above the table, and camera 4 was a fake camera placed opposite to camera 2 to suggest that participants could be observed from multiple angles.

We installed five pairs of speakers around the room, as shown in Figure 1. These speakers were connected to the virtual café to provide spatialized audio. For example, if the remote collaborator moved their avatar to the left side of the café while speaking, their voice would be heard from the speaker that was located on the left side of the room. If he moved his avatar to the table, his voice would be heard from the speakers that were located around the table. In all conditions, participants could hear ambient café noise, the voice of the remote collaborator, and of people in the virtual café.

In a separate room, a research associate sat with three computers play the remote collaborator. One computer showed a top-down view of the virtual table, another allowed him to navigate his avatar in the virtual café, showing his perspective of the virtual world, and a third showed a video feed of the collocated lab. By having these three views, the remote collaborator could act as though the local collaborators were represented as avatars at the virtual table and were then able to walk (virtually) to where they stood (physically). To achieve spatialized audio, the remote collaborator's voice was captured by the computer used to navigate in the virtual world.

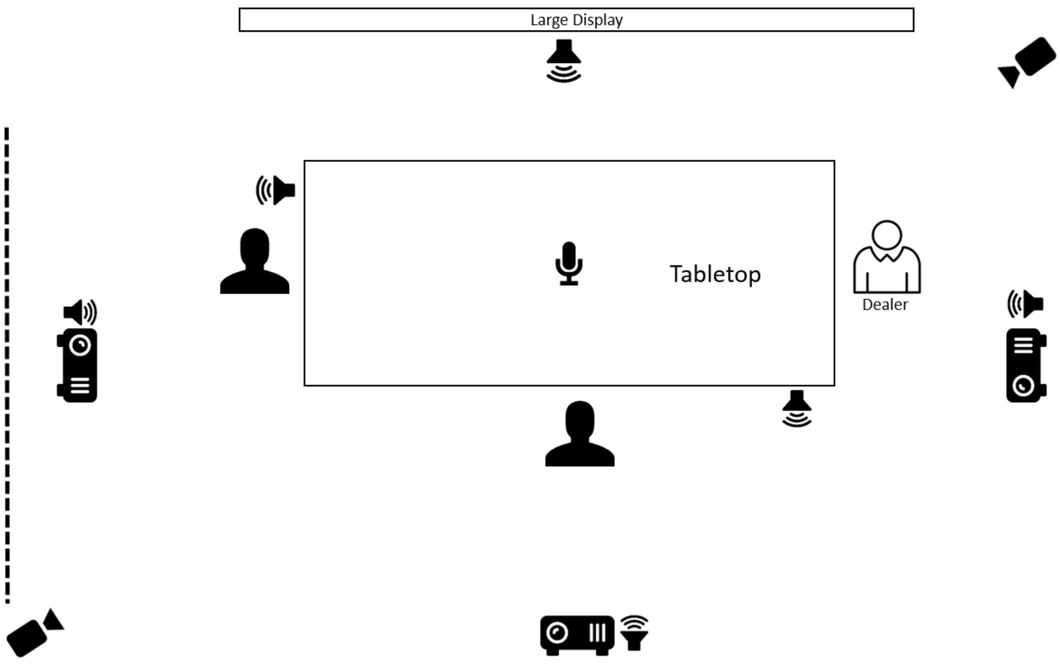

Figure 1: Room setup for the collocated collaborators. Each projector presents one side of the virtual café; the large display shows the virtual tabletop inside the virtual café, and the remote collaborator's avatar could stand behind it. Speakers provide surrounded sound. The camera on the right records the study and provides a live stream for the remote collaborator. The left camera was just a fake camera to induce the feeling of being watched by the collaborators.

Fiducial markers (visual markers that can be recognized by cameras) were attached to all documents (clue sheets, playing cards, and credit card statements) used during the study. A Logitech 1080p webcam was set 1.5m above the tabletop to identify the fiducials. When a fiducial was recognized, the corresponding document appeared on the tabletop display, and on the virtual tabletop in the same position and orientation. Therefore, the remote collaborator could see the document placed on the table. Figure 2 shows the tabletop setup.

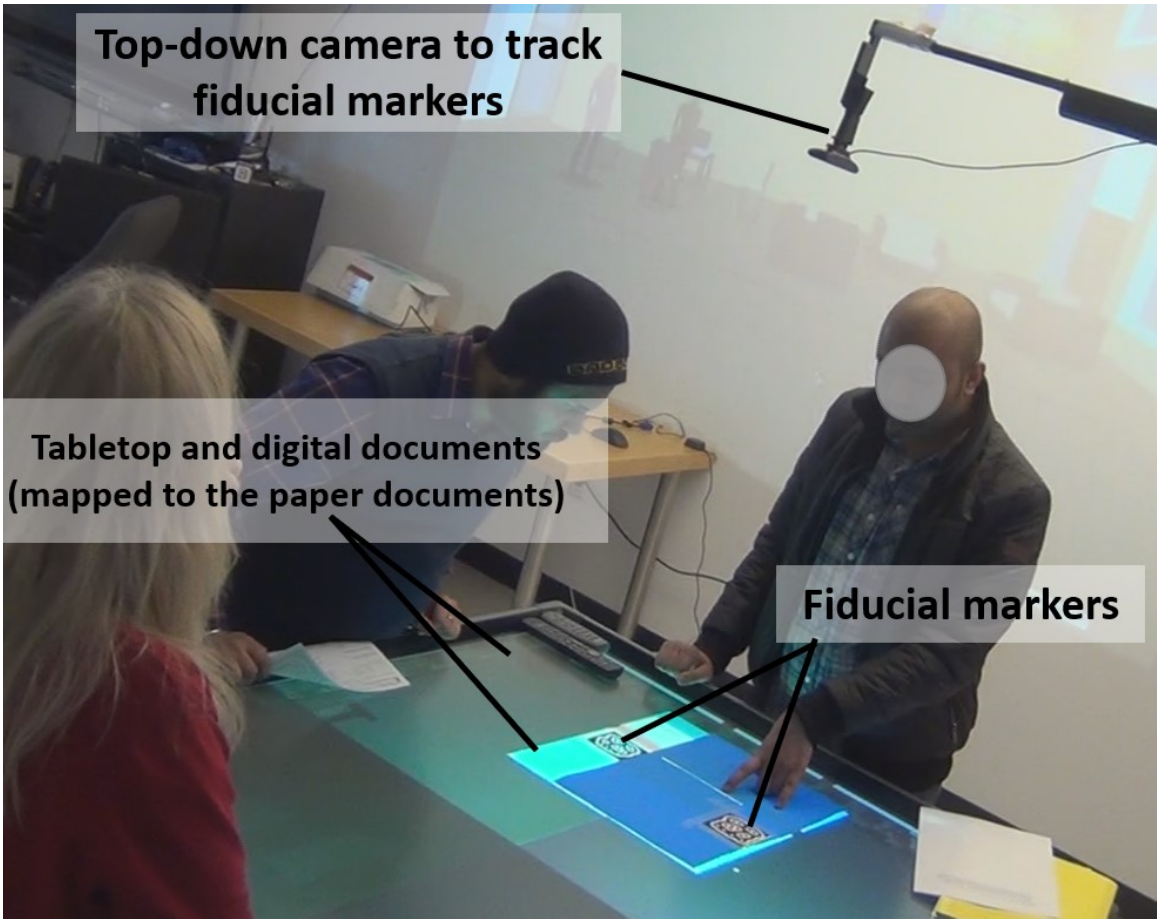

Figure 2: Setup at the collocated location. A top down camera reads the fiducial and sends the results to the server to map the digital version of the documents to the physical documents.

Having a circumambient environment and using an avatar to show the location of the remote participant around the physically-virtually mapped tabletop provides cues for collocated participants for knowing the location of the remote participant. In addition, spatial sounds at the collocated place induce the feeling of having a remote person talking from different distances which could create the feeling of having a remote participant at the same location (co-presence). The avatar of the remote participant mimics actions such as waving and nodding to create the feeling of co-presence with the remote participant and establish engagement at the collocated location.

3.2.2 General Study Design

We recruited Dalhousie University students taking a variety of majors. 16 participant pairs (14 female, 18 males, 19-35 years old) played the part of the local collaborators. Six pairs of participants knew each other. Participants completed a short background questionnaire asking how often they work in groups and how often they share paper and digital documents. Table 2 shows the results of the background questionnaire. In the study, pairs engaged in three activities with the remote collaborator: a card game, a guessing game and a bill sharing activity described in the next section.

Table 2: The results of the background questionnaire

	> 2 times	3-5 times	6-10 times	10-20 times	>20 times	N/A
Work as a group (per year)	4		10	10	8	
Share paper documents (per month)	7	6	13	3	2	1
Share digital documents (per month)		3	9	13	4	3

Aside from saying that the virtual café was connected to the lab and that the remote collaborator could "see them," we did not explain to participants about how the system worked. For example, we did not disclose whether participants were represented as avatars in the virtual world or visible by a video camera, but if they explicitly asked, we told them that we would explain it after the study. We employed this protocol because we wanted to observe which cues participants used to interpret how the physical and virtual settings were connected, to explore what those interpretations would be, and to see if the interpretations had any impact on privacy-related behaviour during the activities. After performing each activity, participants completed a questionnaire asking them to assess their experiences in sharing and hiding their information. We also interviewed both participants together at the end of each activity to learn about their sharing and hiding experiences and their feelings about using the environment for collaboration with sensitive documents. We videotaped the activities.

3.3 Activities and Conditions

We defined two environmental conditions for the study. In the *solo display* condition, participants only saw one side of the virtual café that showed a small extension of the physical table indicating the remote collaborator's place at the table, and a portion of the café visible behind that side of the table. Background café noise could be heard across all speakers, and the remote collaborator's voice was spatialized around the room. In the *circumambient* condition, we projected the café around the physical tabletop on four sides. In addition to the background sounds of the café, participants could also see the activities of other avatars in addition to the remote collaborator and could see their collaborator's avatar if he moved away from or around the table.

3.3.1 Card Game (sharing with all/none)

The activity of playing cards was chosen since many people have well-established practices of how they hide and show playing cards during a game. This activity is an example of a situation in which a collaborator needs to share a document with all the collaborators but hides it from strangers. As noted earlier, these activities are used as proxies for more critical privacy situations found in the physical world. An example of which might be a medical team meeting to discuss a patient situation and a doctor wants to share this patient's medical chart with the team but hide it from other individuals walking around the room.

The dealer (experiment facilitator) and two collocated collaborators stood on three sides of the tabletop, and the remote collaborator's space was displayed on the remaining side. The game played was *31* (banking variant), a turn-based game whereby collaborators try to obtain a total card value as close as possible to 31 without going over. Starting with a hand of 3 cards, collaborators can exchange one or all cards with three cards placed face-up in the centre of the table. Only cards of the same suit are counted in a tally. When a collaborator has 31, believes they have the highest score, or has no more turns, they can "knock." Then the remaining collaborators have one further turn to take before showing all cards to determine the winner. After an open hand played for learning the game and demonstrating the card tracking mechanism, 3 rounds of the game were played.

When physical cards were placed over the table, a digital version of the card appeared on the screen below it (face up or down, depending on how the physical card was held). The card was then visible in the same way to the remote collaborator. The remote collaborator's cards remained face down on their side of the table, but their digital counterparts were displayed face-up on the remote collaborator's table view. When he clicked on two digital cards (1 from his hand and 1 from the centre), the region around the physical cards flashed on the table, indicating they should be exchanged. The dealer then exchanged the physical cards for the remote collaborator. Figure 3(left) and Figure 4 (left) shows the card game setup.

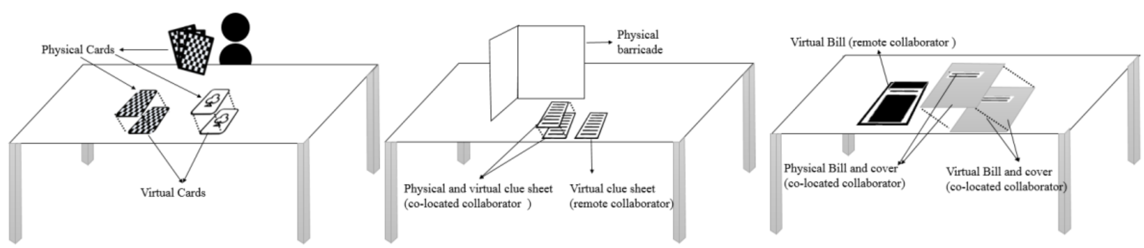

Figure 3: Left: Card game. Middle: Guessing game. Right: Bill sharing.

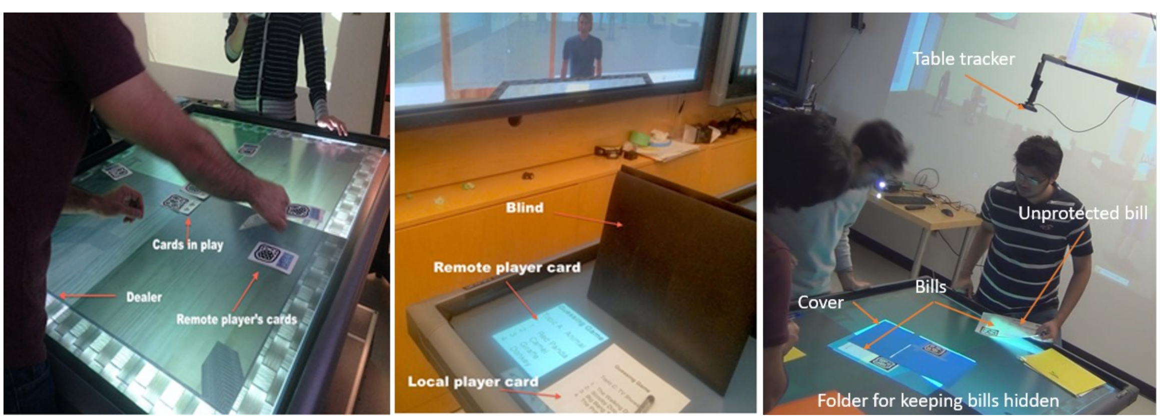

Figure 4: Left: Card game. Middle: Guessing game, Remote collaborator shares their digital list. Three cards placed face down and three cards in front of the large display for a remote collaborator. Right: Bill sharing. Collocated collaborators could use the blue shield to cover credit card statements and the yellow folder to keep their credit card statements inside when not using them.

3.3.2 Guessing Game (sharing with some but not all)

The guessing game was chosen to let us explore each participant sharing and hiding behaviours when they need to share documents with either their collocated or remote collaborator, but not both. Returning to the previous medical example, imagine that the remote collaborator is the patient's psychologist and needs to share some information from the patient's medical history with the head doctor. However, due to the existing privacy policy, they are not allowed to share this information with other team members.

In this activity, two collaborators worked together as clue givers, and the other collaborator played as a guesser. The clue givers each was given five clues about a topic. They began by sharing their clues with each other and deciding the order of the ten clues to give to the guesser. The clue givers aim is to give as many clues as possible before a correct guess is made, while the guesser aims to guess correctly with the fewest clues provided. After the facilitator had described the objective and mechanics of the game, three rounds were played: one where the remote collaborator guessed, and two where the remote collaborator paired with one of the collocated collaborators as a clue-giver. For each round, collocated participants were given their five clues on a single printed sheet. When playing as a clue-giver, the remote collaborator identified where on the table to place his digital clue sheet using their virtual table display. A physical blind was used to hide the physical and digital clue sheets when a collocated collaborator was guessing the topic. Physical clue sheets were tracked using fiducials, and when placed on the table a digital version was displayed below it on the table at a slight offset. When the remote collaborator was guessing, collocated participants could hold their clue sheets away from the table so that they were not tracked. Figure 3(middle) and Figure 4 (middle) showed the setup for the guessing game when a collocated participant played as guesser.

3.3.3 Bill Sharing (a portion of a document with all)

The bill sharing activity was devised to let us explore participants' sharing and hiding behaviors while sharing just a portion of a document with other collaborators. For an equivalent real-world scenario, we return to the medical example: the psychologist needs to share comments from a patient's immediate family about the patient's medical history with all the members of a team, so they can reach a decision concerning the next stage of therapy. But due to the existing privacy policy, the psychologist cannot share the names with the medical team, so parts of the document need to be redacted only to share a portion of each document. Figure 3(right) and Figure 4 (right) showed the setup for the Bill sharing.

By using simulated credit card statements, we aimed to convey the confidential nature of the documents to the participants. We asked participants to imagine that they were roommates, and they met to figure out some expenses for their apartment. In this scenario, each participant was given 3 fake credit card statements and was asked to share specific payments for different bills paid on their credit cards. Personal or private data were to be shielded from the others in the group. For this purpose, we provided a physical slit sheet (a covering sheet with a 2 cm horizontal slit in the center) enhanced with a fiducial for the co-located participants to use. Using the cover shielded both the physical and digital copies of the credit card statement. This mechanism was quite far from normal physical privacy techniques (for example, using one's hands or folding to hide portions, blacking out regions with a marker), yet it permitted a straightforward technical way to translate physical sharing into virtual sharing. When the remote collaborator shared a statement, it was displayed in the center of the table with sensitive details blacked out. After the facilitator introduced the scenario and demonstrated the use of the cover, participants conducted 3 rounds of this activity. In each round, each collaborator needed to show one or more items from their
3.4 statements. Figure 3 (right) and 4 (right) shows the setup for the bill sharing activity.

3.4.1 Results

Questionnaires

After performing each activity participants completed a brief questionnaire consisting of five 5-point Likert-scale questions (anchored with Strongly Agree and Strongly Disagree, see Table 3: Post task questionnaire). We ran one-way ANOVAs on the responses from the guessing and card game's questionnaires separately, regardless of display condition.

Table 3: Post task questionnaire

It was easy to hide documents from the other person at the table.

It was easy to hide documents from the remote person.

It was easy to share documents with the other person at the table.

It was easy to share documents with the remote person.

It was easy to tell if there was someone near me or near the table in the virtual Cafe.

We found no main effect of display condition on responses to any questions. A significant effect of activity was found only for hiding documents from the player at the table ($F\ (1,32) = 15.328$, $p<0.001$), with the guessing game viewed as more difficult. An interaction effect (display X activity) was found for hiding documents from the remote player ($F\ (1,32=5.282$, $p=.025$), with more difficulty perceived in the circumambient condition for the guessing game. We anticipated but did not see an effect of display condition on the last question ("…tell if there was someone near me…").

We next considered differences in ratings for ease of sharing and hiding documents with collocated and remote collaborators, regardless of display condition. We did not find significant differences for the card game. For the guessing game, there was a significant difference ($F\ (1,32) = 11.029$, $p=0.001$) in ratings for hiding documents: participants found it easier to hide the clue sheet from the remote collaborator. There was also a significant
3.5 difference ($F\ (1,32) = 13.086$, $p=0.0005$) for sharing: participants found it easier to share their clue sheet with the local collaborator.

Qualitative data analysis

We coded the video for qualitative data analysis. First, several researchers conducted open coding on a small sample of videos and met to discuss observations. From this, a set of codes was derived to be used in a second pass, this time covering videos for all groups. We coded low-level details such as the way collaborators held documents and the direction of their gaze, annotated high-level observations such as strategies they employed to conduct the activities and transcribed conversations and any questions asked.

Card Game

Our results suggest that the fiducials on the cards did not impact privacy related behaviors in a significant way, and that the digital shadows enforced physical-digital correspondence. 3.5. Out of a total 193 card-exchanging events, no participants covered the marker of the card they wanted to exchange while they were extending their arm over the tabletop. During exchanges the player's card was being tracked, but the digital shadow appearing on the table corresponded to whether the card was held face up or down. Similarly, in the nine cases where participants exchanged a card but changed their mind, it was apparent by whether their card was held face up or down whether they had revealed one of their cards to both players.

As with exchanging cards, the broader physical behaviours of our participants largely corresponded with how people play cards around a table.

We also did not observe participants acting any more protective of their cards in the circumambient or solo display conditions. 23/32 participants (10 participants in solo display and 13 participants in circumambient display) leaned over the tabletop to exchange their cards. These participants held two cards in one hand and held the card they wanted to change in the other. They were careful to keep the two cards close to their chest before they leaned over the table. They then drew away from the table and lowered their cards from their chest at the same time. In two cases two participants (one participant in the solo display and one participant in the circumambient display) hesitating before placing cards on the mixed presence table.

The remaining nine participants (six participants in solo display condition and three participants in circumambient display) moved their hand over the table first, then leaned over the tabletop and brought the hand close to their chest. Therefore, the system could detect the cards for a moment and show the virtual cards that corresponded with real cards on the table. Only in one case, the participant noticed that his cards were being tracked and said "*oh*". The other participants concentrated on changing cards and did not notice that corresponding virtual cards appeared on the table. We also noted that 14/32 participants at least once rested their cards on the edge of the table during the game. This position limited the co-located opponent's ability to see their cards but increased the possibility of revealing the fiducial to the table tracker unintentionally.

3.5.2 Guessing Game

The absence of fiducials seemed to influence behavior in the guessing game. When the remote player was the guesser, most (14/16) groups put their clue sheets directly on the tabletop. Fiducial markers were not placed on the clue sheets when co-located collaborators worked together, and it seems that participants interpreted this to mean that the remote collaborator would not be able to see them. Fiducials *were* used when one of the co-located participants was guessing. In these cases, an opaque plastic barrier was used to block the virtual and physical clue sheets from the guesser's view; all co-located teammates put their clue sheet on the tabletop beside the remote collaborator's virtual clue sheet, behind the divider. On occasion, the fiducial would not be tracked due to occlusion by the barrier, and so the clue sheet's digital shadow would not appear. Participants did not remark when this occurred, relying instead on feedback from the remote collaborator indicating that they could see the sheet.

As for broader physical behaviours, these were evident and reasonable in relation to local collaborators, but generally absent in relation to the remote collaborator. Most (26/32) guessers stood away from the tabletop while others were working on the clues with the remote collaborator, to ensure they couldn't see the clues, sometimes making themselves busy by looking at their cell phones, talking with the facilitator, or looking at the virtual world. When the remote collaborator was guessing, the participants moved together at the corner of the tabletop to decide on the order to give the clues. Most groups did not pay much attention to the location of the remote collaborator's avatar when he was guessing, however one group was noticeably vigilant about the location of the remote collaborator when he virtually walked around the café. Participants in this group stood shoulder-to-shoulder, to protect their documents from being seen.

3.5.3 Bill Sharing

We observed different behaviors in placing/ removing bills on the table and participants did not have a consistent method of performing this action. During the bill sharing activity, bills had to be shared/removed on/from the tabletop 96 times.

Placing the bills: In 60 cases, 25 participants put their credit cards statements on the tabletop when hiding fiducials with their hands. However, everybody around the tabletop was able to see the credit card statement until it was hidden under the cover. In 21 cases, 7 participants first hid the bills under the cover and then put the covered bill on the tabletop, so nobody could see the statements. In 15 cases, 12 participants became confused with using the cover, and they removed it several times from the credit card statements so that the other collaborators were able to see the information. All these participants forgot to keep the credit card statements' fiducials hidden while they were fixing the cover.

Removing the bills: In 28 cases, eight participants removed both credit card statement and the cover from the tabletop together. In 36 cases, 21 participants removed their statements and left the cover on the table. In 9 cases, 4 tried to remove their statement as fast as they could so no one could see their private information. In 20 cases, 15 participants put their hands over fiducials before they removed the statement from the tabletop. In 10 cases, 4 participants removed the statement without covering the fiducial or any part of the credit card statement.

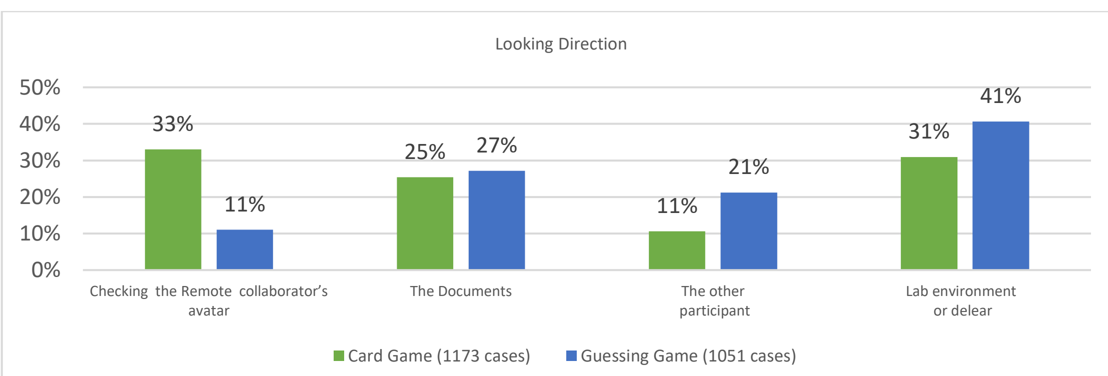

Figure 5: Looking Directions.

Attention

Looking directions in all activities: We observed that participants looked in different directions around the study room while performing activities. Figure 5 shows the result of our observations concerning the directions collaborators looked during the study. We were 3.5.4 interested to know where participants were looking and if they paid attention to the mixed presence collaborative environment. This was important because visually exploring the environment may help to build a mental model. Using cues such as cameras, projectors, and virtual people provide us with information that could help us to explore how participants build a mental model and which cues have more impact on them.

In the circumambient condition, we observed that 10/16 participants (during the guessing game) did not pay attention to the environment or moving avatars and only concentrated on the game. These participants might look around a few times or check the setup, but they did not look with curiosity to learn about the system nor have any comments or questions. They usually occupied themselves with activities such as checking their cell phones or talking to the facilitator until it was their turn to play. The remaining participants explored the setup and asked questions about the setup and the projected café while sharing their ideas and assumptions with others, *"how the system works? You can set up a private server?"–p18, "it is neat to be avatar"*–p19, *"I think he can see us as an avatar like we are seeing him"*–p15, *"it is cool to do a high five on the table with Brian [remote collaborator]"*–p23. In the solo display condition, none of the participants showed any sign of interest in exploring the setup; they also did not ask any questions to learn about 3.5.5 the setup or what remote collaborators can see.

Scripted Events

The remote collaborator always joined the study after the collocated participants stood around the tabletop. The remote collaborator talked with the facilitator walking toward the virtual tabletop and participants could hear him from different speakers.

When the remote interrupter appeared at the end of bill sharing activity to talk with the remote collaborator, 9/16 groups (4 groups in solo display and five groups in circumambient) asked if the interrupter could see them. For example, *"He can see us?"–p10,* they would like to know how he was connected to the environment or if he was a real person. *"Brian was in a real cafe?"–p5 "From where he comes?"–p6.* The remaining participant pairs ignored the interrupter and kept working with the credit card statements.

3.5.6 Interviews

After each activity, we interviewed participants to talk about their sharing and hiding experiences. Table 4 summarizes the results of the interviews. During the card game, 25/32 of participants found sharing equally comfortable with both their collocated and remote collaborator. However, 18/32 participants tended to find it easier to hide from the remote player. For the guessing game, 17/32 participants found it easier to share and hide the clues from the remote player. These results are consistent with the outcome we had from data analysis of questionnaires.

Participants found sharing parts of the credit card statements easy with both the collocated and remote collaborator but found it easier to hide parts of the statements from the remote collaborator.

At the end of the study, we asked participants about their preference for the two conditions and if any of the conditions helped them to increase their awareness of the events that were happening around them. 22/32 participants preferred the circumambient condition during the card game and guessing game. They liked the circumambient condition because it helped them feel more immersed in a real café with other people. For example, *"I think the whole view is cool. It feels like you are in the location with the person"–p30, "I can talk to him see him. It kinda feels like a real world."–P17, "I think, when we could see an entire cafe, it makes you feel closer to the person regardless of the physical distance between you, so if I want to share something with somebody who is not necessary for the same area, this will make it more real."–p29.* Even though many participants seemed to like the circumambient condition for the enhanced immersion, they did not see the correspondence as a medium for visibility and sharing.

Table 4: Result of hiding and sharing from interviews

Action		Card Game	Guessing Game
Hiding	Easier from collocated	2	6
	Easier from remote collaborator	18	17
	Same with Both	12	9
Sharing	Easier with collocated	6	5
	Easier with remote collaborator	1	17
	Same with Both	25	8

14/32 participants thought it was not necessary to have the circumambient condition when sharing confidential documents. However, for activities such as card game and guessing game, the circumambient condition was useful: *"However, it is good when you want to socialize but for sharing information, or when you want to get down to business, I think you don't need this [circumambient condition], and just front view."–p29, "it is ok, I didn't feel anything, because it was a game, it wasn't something that I would be asking him about his personal life"–p13; "I'm sharing my personal information and I have the feeling that this information might, or some other people might hear this information but for card games guessing game it is not."–p31.*

11/32 participants mentioned that if turning the projectors off in the circumambient condition meant that people in the virtual environment could not view their documents, then they would prefer to share confidential documents with the projectors off (i.e., in the solo display). However, if turning the projectors off did not make a difference in what the virtual people could view in the café (i.e., their documents) then they preferred the projectors on so that they could keep track of the remote collaborator and other people's locations in the virtual café. *"If they can see my cards then just front view"–p28, "if it is a big game, or money or gambling is going then yea just front view"–p22, I don't want only one screen so I can see who is over there but if I only see one screen so do they still can see them[the documents]"–p16.*

4/32 participants preferred the solo display condition so that they could concentrate on the activities, “I think the front view is fine, I really didn’t use the other views.” P11, “I think only usable stuff here is this monitor”–p24, “I like front view, I don’t care about the projected cafe.”–p12. 6/32 participants did not have any preferences regarding this.

A slight majority of participants found it easier to hide their documents from the remote collaborator (18/32 for a card game and 17/32 for guessing game and 20/32 for bill sharing) compared to collocated participants. From the comments, interviews, and observations it is apparent that some participants believed that the remote collaborator could only see their documents if they chose to show them over the tabletop. For example, *“He couldn’t see my hand* [Cards]*”*– p2*, “he is not here, and he cannot see my cards”* – p3. They also thought that it was easier to hide documents from the remote participant because he would not have a chance to look at their documents even if they held them improperly. For example, *“there is some chance for a real person to see my cards but there is no chance for him [the remote collaborator]. Very secure”* – p7*, “in actual world p1 can see my cards, for example, if card drop from my hand, but for virtual, there is no chance”* – p23.

3.6 Discussion

In a dialectic process, privacy regulation is formed from our expectations and experience with and observation of other collaborators’ behaviours [142]. In a dynamic process, privacy forms through continuous negotiation and management, and boundary definition for collaboration under different circumstances [142]. In both dialectic and dynamic processes, privacy constraints formed through interaction with other collaborators plays a role in establishing or enhancing presence. Our strategy was to retain the tangible nature of cards, clues or credit card statements and take advantage of the privacy–related protocols that have emerged with the physical cards, bills and documents, while designing a relatively unconstrained space for mixed presence collaboration; therefore, users are able to manage their privacy as a continuation of their experiences in similar situations.

3.6.1 Mapping physical Privacy Behaviors

Mixed reality collaborative environments are still quite rare, and there is no commercial example in use by the public. Therefore, individuals usually do not have enough collaboration experience and knowledge of a mixed presence collaborative environment. For example, there is a deficit of knowledge about how the mapping between physical and virtual documents works, how they can be aware of events and changes in the environment if there is any mechanism to increase their awareness and how they can use them. This lack of experience makes it challenging to manage privacy simultaneously in both physical and virtual environments [87]. The background questionnaire indicated that only 3 participants had heard about mixed presence, and none had experienced it.

Deploying well-practiced physical interactive methods and actions in virtual environments minimizes or potentially even removes the learning stage and provides a more integrated collaborative environment between the virtual and physical world. Our observations suggest that collaborators can efficiently use a mixed presence collaborative environment that translates physical privacy behaviours into virtual actions even without previous collaboration, though issues exist.

First, technology can impact the physical behavior to the point where it is no longer obviously secure in either the physical or virtual spaces: some participants did not like to use the slit sheet during bill sharing for this reason: *"I didn't feel as secure as [when] we played the games, On the last bill I had to hide purchasing form the Best Buy [name of a store] and when I put my paper down, or start sliding the paper [shield] over; I had to instantly have my hand covering the marker, but I may actually show something that I don't want him to see"* –P5, *"the guy next to me can easily look at my bill."* –p23.

Second, accidental exposure of private documents needs to be flagged appropriately, or else it can quickly go unnoticed. In our study, we observed many unexpected incidents such as leaving physical documents unprotected under the view of the tracking system which resulted in exposing the collaborator's information. In many cases, it was not evident that local collaborators noticed the breach.

3.6.2 Managing Privacy and Security across Multiple Spaces

After examining the interview responses and coded video data, we classified the results into three main categories. These three categories can be used as necessary guidelines to design a mixed presence collaborative system to help collaborators build a mental model and trust the system. Our findings are in line with guidelines for privacy in mixed presence suggested by Reilly et al. [32] and Dix et al.'s [53] definition of the three spaces in mixed presence environments.

The relation between physical and virtual spaces: Many collaborators showed interest to learn how their actions were manifested in the virtual world, and if they needed to do anything specific to protect their document; this is the sensed space of Dix et al. [53]. We tried to provide different cues to help collaborators to understand the transference of their action between the mediums.

The participants' comments and activities imply that they likely assumed that the remote collaborator's view was limited to the tabletop so that hiding from the remote collaborator is more comfortable and safer. Even when they did not protect the document well (e.g. drop it on the floor), the remote person could not see it. For example, *"because the only information which I was trying to share [on the table top] ...I am sharing only that information [on the tabletop] it was perfectly safe for sharing.", "only when I put them on the table he could see that"– p3.* Also, 12/16 groups mentioned at different times that they would like to know what the remote collaborator could see so that they could trust the system to manage their privacy.

Virtual space: Collocated collaborators showed significant interest in learning how they were presented to the remote collaborator. For example, they asked if the remote collaborator saw them as an avatar inside the virtual world or if the remote collaborator saw their real faces. The remote collaborator commented on what the collaborators around the table wore, and there were cameras set up around the physical room. *"I don't [feeling safe] because I don't know what other participants [remote collaborator] can see." – p11, "I wish I could see what he was seeing to confirm what I am sharing"–p31.*

Physical space: After quickly establishing the boundaries of the shared work region in the collocated space, almost all participants asked for details about their remote collaborator's physical environment. While our mixed presence collaborative environment was designed as a combination of one virtual and one physical space, our participants based their trust partly on an understanding of the remote collaborator's physical context. Collocated collaborators wanted to know where the remote collaborator was physically located, e.g., where they in their office, a private room, a meeting room, or in a public place like a library or a café. Participants also asked if the remote collaborator was alone, or if anybody else was in the same location. We provided cues to make the café feel like a public environment. For example, we explained our mixed presence collaborative environment is shared between different universities for collaboration. We also had one of our researchers enter the virtual café and interrupted the study while pretending to know the remote collaborator. Even so, collocated collaborators wanted to know more about what was happening physically on the other side. *"he can google the answers."*–p4, *"I don't know if he is alone. That is my only concern."* – p12.

3.6.3 A Classification of Correspondence Cues

From our video coded analyses and interviews, we learned that collaborators start the activities with a mental model close to their previous collaboration activities such as display sharing and video conference collaborative environments. However, they continually updated this mental model by seeing different cues that we provided during the study.

Visible or audible sights of interaction are considered as consequential communication. Accompanying Baker et al.'s [42] categorization of consequential communication, we classified cues in MR-MP into four groups.

Responsive cues: In a physical environment people expect specific results for their actions. Responsive cues follow from a collaborator's actions in the physical space. For example, in our prototype, if a collocated collaborator put her document on the table, the system displayed the digital version on the table to indicate it is also visible to those "nearby" in the virtual world.

Environmental cues: These are cues in the environment that help collaborators build an understanding of the mixed presence environment. For example, we used spatialized audio to give collocated collaborators a sense of "where" the remote collaborator was relative to the table.

Event-based cues: These are events that reinforce aspects of the mixed presence environment (e.g., interruption of the experiment by a 3rd party reinforced that the virtual world was a public space).

Communication-based cues: These are cues that directly address collaborators and can have a profound impact on their mental models. For example, when the remote collaborator waved to collocated collaborators, most waved back while looking at the avatar. The remote collaborator's comments on their dress or actions strongly reinforced the idea that they were visible.

In our study, unexpected cues which break people's focus on a collaborative activity and cues that infuse the feeling of being insecure had a more significant influence on collaborators than ambient cues such as spatialized audio and background activities. However, such "ambient" cues were enough for some participants to become aware of their environment or more cautious about their actions. *"We could hear his sound…. so, this is good to see he is walking around;"* – p2, *"If I don't exactly understand how the virtual room works if someone else joined this room and they are standing over there can they see what is on the table?"*– p7*, "how we can know that virtual person, standing by the table or next to us?"*– p8.

3.7 Main Contributions

We contribute three primary observations from this study:

- Our findings indicate that designers of MR-MP systems need to carefully consider mechanisms to help collaborators increase their awareness of events that are happening around them in both physical and VEs. Mechanisms should also be in place to help reduce accidental exposure. Building on existing physical privacy behaviours is one way of doing this, however collaborators will still require assurances that privacy and security are maintained during document sharing.
- Collaborators actively seek information about the physical and virtual space, tools, and interactions, and the relationship between physical and virtual spaces, tools, and interactions. We identify four types of cues that collocated collaborators use to construct a mental model: responsive cues, environmental cues, event-based cues and communication-based cues.
- We illustrate that it is difficult for collaborators to trust an MP collaborative environment unless they can verify the completeness of their mental models.

CHAPTER 4 EXPLORING GROUP AWARENESS IN AN IMMERSIVE MIXED REALITY ENVIRONMENT

Dourish and Bellotti [34] explained that awareness (social awareness [143] [144]) is shaped by the availability of people and their presence (for example questions such as Who is available? who is around?). Awareness and presence are interwoven. While it is possible to study these concepts independently, our study approaches them as a unit i.e. stronger awareness reduces presence disparity and vice versa.

We started our research by looking at privacy in a mixed reality environment and physical practices for hiding, sharing and showing information during collaboration and while performing activities such as document sharing and playing games. This confirmed that privacy must be managed in the virtual and physical environment simultaneously when working in a mixed presence environment. Collaborators use mental models close to their previous collaboration experiences such as display sharing and video conference and they continually update this mental model by examining different cues. We categorized four groups of cues that help collaborators to update their mental model and awareness: responsive cues, environmental cues, event-based cues and communication-based cues.

Our first study showed that collaborators are less comfortable in an environment that does not provide them with enough cues to increase their group awareness and provide them with a strong feeling of involvement. For example, in the first study and during the solo condition (no circumambient projection on walls), the remote person could walk around the virtually-physically mapped tabletop and see the documents that collocated people were working on. Our participates mentioned in the interview that they felt uncomfortable when the remote person could walk and see their documents, but they could not see where he was standing.

We explained the limitations of our previous mixed presence environment and why using it in this study would have limited us from exploring and investigating awareness and presence. The key limitations were:

1) The system was designed to study sharing and hiding documents. Remote and collocated collaborators did not work on the same document.
2) The experimental design and system prototype focused on the experience of collocated collaborators; we did not evaluate the experience of remote collaborators.
3) In our initial study, we looked at preserving physical document-centric behaviour in the collocated space while connecting to a remote collaborator (hybrid physical-digital documents). The aim was to preserve embodied and physical interaction with documents in the collocated space. Collaborators were limited to using 2D documents.

We used a setup that allowed us to explore awareness and co-presence around an interactive touch tabletop in a collaborative setup that showed progress from a symmetric to asymmetric setup. We considered three collaboration scenarios involving 3D object manipulation around a physical-virtual mapped tabletop. We used a Tabletop condition as a Strict WYSIWIS that provided a symmetric setup and two immersive virtual reality (VR) conditions that a used Relaxed WYSIWIS idea which provided different degrees of asymmetry in the collaborative setups. The new setup allowed collaborators to work on shared 3D models while the previous setup was limited to mapped physical-digital documents.

Also, using an HMD and immersive virtual environment contributes to creating the feeling of co-presence. For example, remote collaborators can be in a virtual model of the collocated location. Collaborators show higher levels of satisfaction from Face-to-Face interaction [145]. When people are collocated with others, they naturally speak to each other and share awareness information through face-to-face interaction. The system we designed could be used with multiple collaborators when they were wearing an HMD, but we decided to only use an immersive environment at the remote location and allow collocated collaborators to have Face-to-Face collaboration. This also allowed us to explore a situation in which a collaborator used an HMD and immersive environment while other collaborators utilized a touch tabletop. We were interested in 3D objects as well, as they are in a sense a more "natural" collaboration medium for immersive 3D virtual environments.

We first explain our research questions, and then we provide the details of our second immersive mixed reality collaborative environment. Next, we describe the study design.

4.1 Research Questions

The first research question defining this study and informing our overarching investigation into awareness and presence in immersive collaborative environments is:

- Can using an IMRCE that provides an asymmetric MR collaborative environment for collaborators help collaborators to increase their group awareness and the feeling of co-presence while working on shared 3D objects?

The results of the study showed that using an immersive virtual environment made a significant difference in increasing group awareness and maintaining the feeling of co-presence of collaborators while working with each other using VR and a physical tabletop. Also, the collaborators described themselves as more engaged in the group dynamic when the remote collaborator used a VR environment.

We also investigated the impact of the remote collaborator working with a field of view that is the same as or different from that of collocated collaborators around the physical tabletop on the group awareness and presence. Therefore, our second research question is:

- Whether using different projections of 3D models on or above the virtual tabletop and inside an immersive environment to manipulate 3D models makes a difference for group awareness and feeling of being co-presence.

The results of the study indicated that the method of representing 3D models in a virtual reality environment did not make a significant difference in the collaborative experience. Projecting 3D models over the virtual tabletop did not increase group awareness nor decrease the presence disparity in comparison to presenting 3D models within the virtual tabletop.

More generally, our findings show that using IMRCE could be a solution to increase the feeling of co-presense in participants and improve group awareness during collaborative activities such as training, brainstorming, and social meetings.

Environment Setup

Group awareness is essential since it plays a crucial role in fostering mutual understanding and clarity to group activities, preventing conflicts and misunderstanding and improving
4.2 productivity. We identified four types of cues in the first study (details in section 3.6.3).

In the new design, we used different technologies to provide cues from the four categories. For example, we used position tracking [146][147][148] to track the location of collaborators around the tabletop, we used hand tracking [81][98][102][99][101] to show the position of hands around the 3D model, and we used hand embodiments to help collaborators increase their group awareness.

We use hand embodiments and position indicators to provide real-time information (i.e. collaborators' locations and their hand positions) so that both collocated and remote collaborators can be aware of other collaborators' activities and location. For example, when a hand embodiment is an object, collaborators can assume that someone is working on the model.

There is substantial evidence of immersive VR's benefits in areas such as phobia therapy [149][150], military training [151][152] and entertainment [153][154]. Using 3D models lets us utilize the capability of an immersive environment and a head-mounted display (HMD) for interaction and manipulation of the remote collaborator's sense of co-presence. We used an immersive virtual environment to provide a model of the collocated space for the remote collaborator and provide them with a similar (not exact) field of view to that of collocated collaborators.

4.2. Touchscreen Tabletop Setup

Collaborators stood around a physical touchscreen tabletop to work on the given tasks and collaborate with a remote collaborator. We had a physical tabletop at both collocated and remote locations. In the remote location, the physical tabletop served as a proxy for the touchscreen tabletop in the collocated location; the remote collaborator could use it to orient themselves while wearing the HMD as though they were “at the table” with their collaborators. We believe this configuration introduces a reasonable real-world use case, where a remote collaborator does not have access to multitouch tabletop displays at their location but does have access to a (non-interactive) table. We installed a hand tracking sensor on the edge of the physical tabletop to detect collaborators’ hand movements and positions while they extended their hands over the physical tabletop. We exchange hand movements and position data over the network to map hands to their hand embodiment on the counterpart location. A top-down tracking system was installed over the physical tabletop to track the location of collaborators relative to the physical tabletop. Our system mapped each person around a physical tabletop to an indicator inside the immersive environment or on the physical tabletop at the counterpart location. Our system mapped each person inside the collocated space to an indicator inside the immersive environment or on the physical tabletop at the remote location. Figure 6 shows a sketch of hardware setup at the collocated location. Figure 7 (top) shows the actual setup at the collocated location.

Users around the physical tabletop could change the position of a 3D object by using one finger, change its orientation by using two fingers, changing the scale by pinching out with three fingers. The initial contact should happen on the 3D object, however, as far as one finger stays in connection with the 3D object, other fingers can move on the touch display. Collaborators could see an indicator on the physical tabletop showing the location of the counterpart collaborators relative to the tabletop. Also, we used 3D hand embodiment on the physical tabletop to visualize the position of counterpart collaborators’ hands.

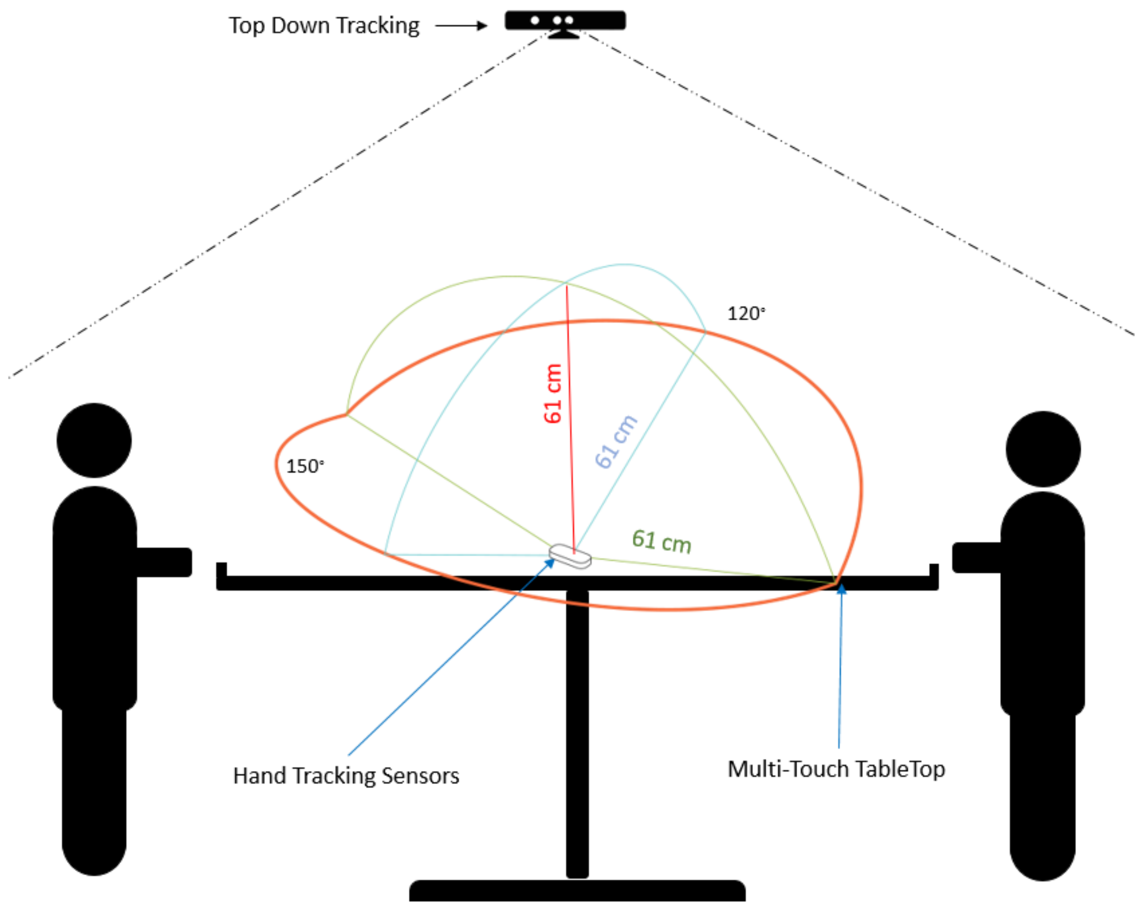

Figure 6: Collocated setup. Collocated collaborators use a touch tabletop to manipulate 3D models. Hand tracking sensors track their hands' positions and map them to their virtual hand 3D embodiments at the remote location (on the virtual or physical tabletop).

4.2 Virtual Environment Setup

The remote collaborator wore a Head Mounted Display (HMD, Oculus Rift Consumer Version 1) and stood before a physical tabletop. We tracked the location of the remote collaborator relative to the physical tabletop. We also tracked her hand positions when she was extending them over the tabletop. We provided an immersive 3D model of the collocated location and a virtual tabletop that was linked to the physical tabletop at the collocated location. The remote collaborator wore a head-mounted display and connected to the collocated location through the immersive virtual environment. Figure 8 shows the collocated location and the immersive environment side-by-side.

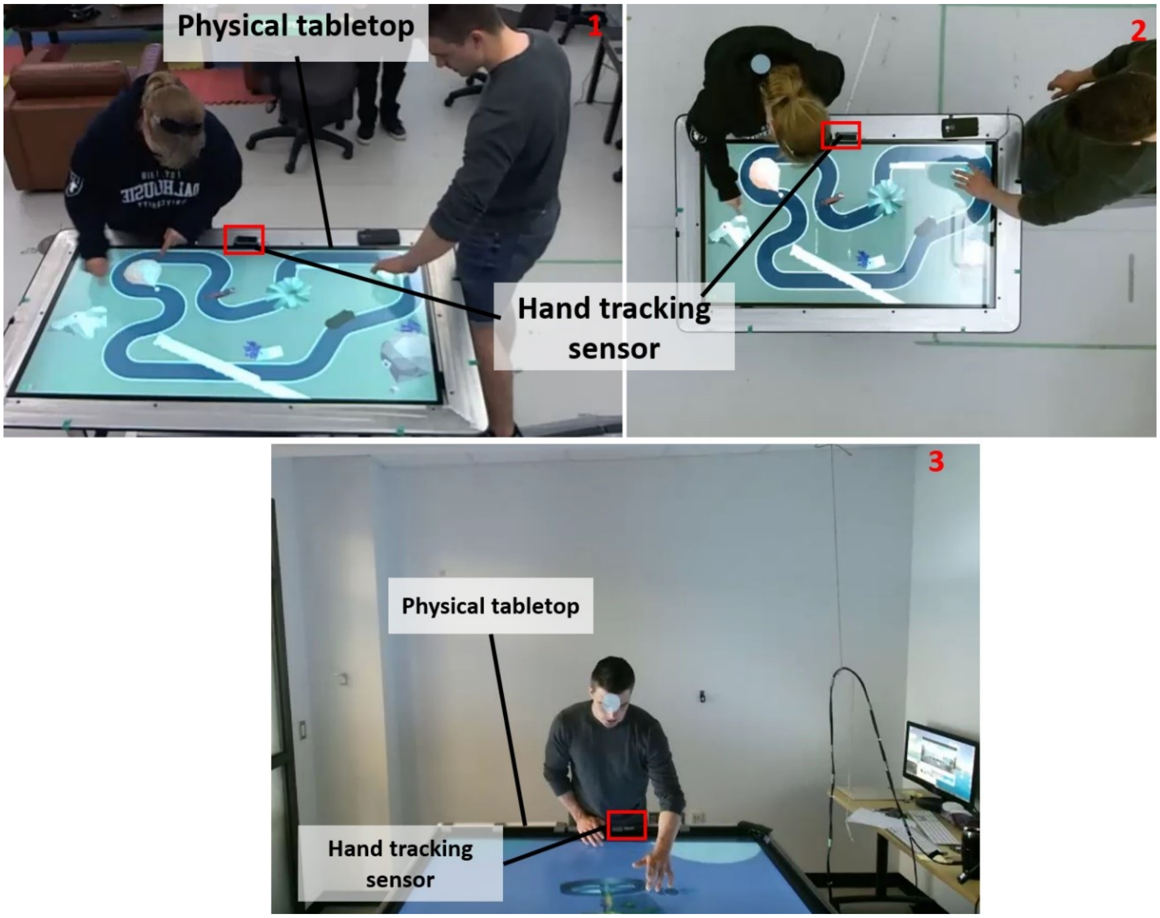

Figure 7: (1,2) physical tabletop at the collocated location. (3) physical tabletop at the remote location.

Figure 8: (1) physical collocated place, (2) immersive virtual room.

In this setup, the physical tabletop acted as a reference structure for the virtual tabletop. The virtual tabletop was aligned with the physical tabletop. In other words, when the remote person touched the virtual tabletop or put their hands on the edge of the virtual tabletop (inside the immersive environment), they would also touch the physical tabletop.

The physical tabletop at the remote location was bigger than the physical tabletop at the collocated location. We made sure that the two tabletops (virtual and physical) were correctly mapped to each other. The remote collaborator could see hand embodiments that were mapped to collocated collaborators hands. We used simple indicators inside the immersive environment to present the location of people at the collocated location for the remote collaborator. Figure 9 (1,2) shows the view of virtual tabletop inside the immersive environment while the remote participant was bending to reach a 3D object, and (3,4) shows the position indicators and collocated participants around the physical tabletop.

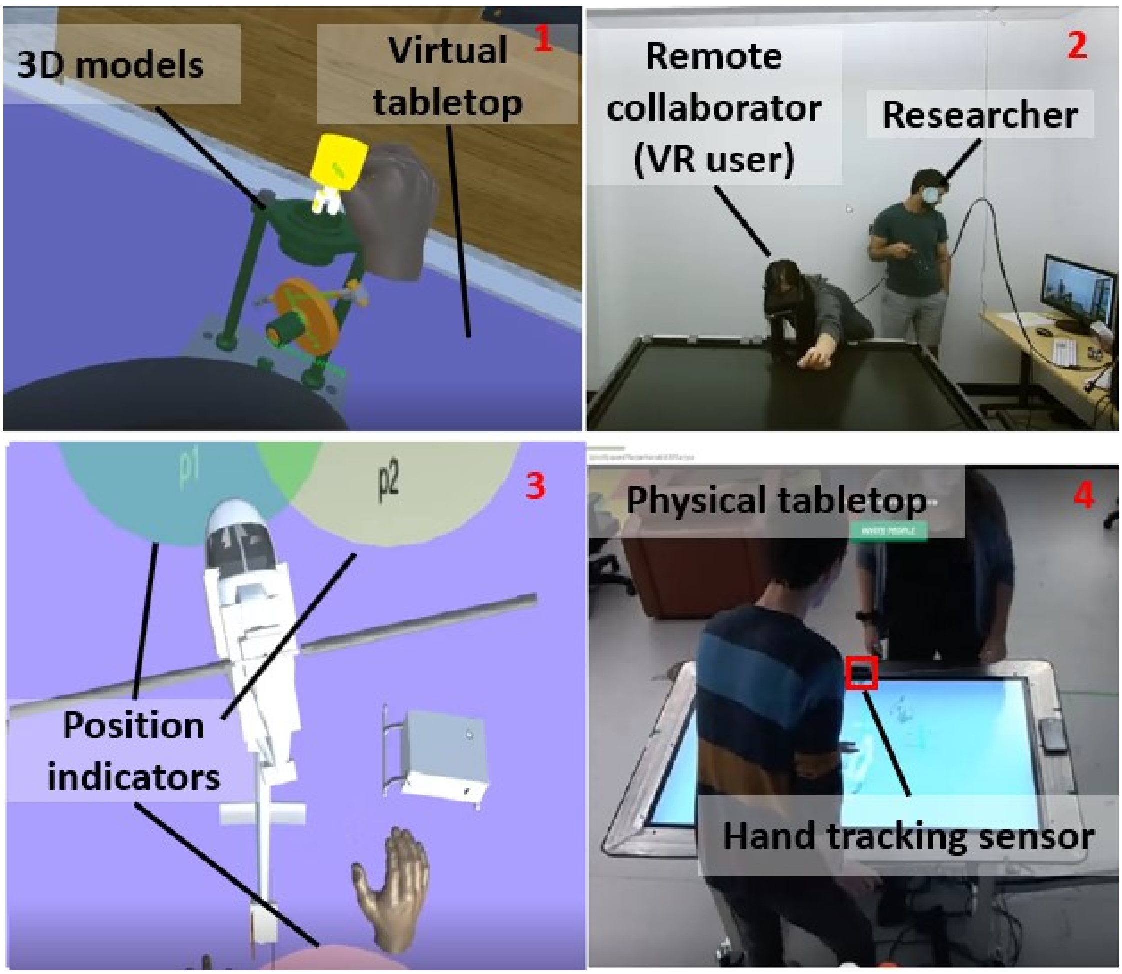

Figure 9: (1) Virtual tabletop and virtual hand of the VR user, (2) The remote participant at the remote location (3) The position indicators and virtual hand (4) The collocated participants around the physical tabletop.

4.3 Study Conditions

We have defined three conditions for the study. Collocated collaborators used a physical tabletop in all three conditions, which was the only method to collaborate with the remote person and work on the shared data. Face-to-face communication is still preferred over digital communication for collaborators to benefit from nonverbal communication [155]. Therefore, we use the HMD only at the remote location. Figure 10 shows the set up at the collocated location. The remote collaborators experienced three different conditions.

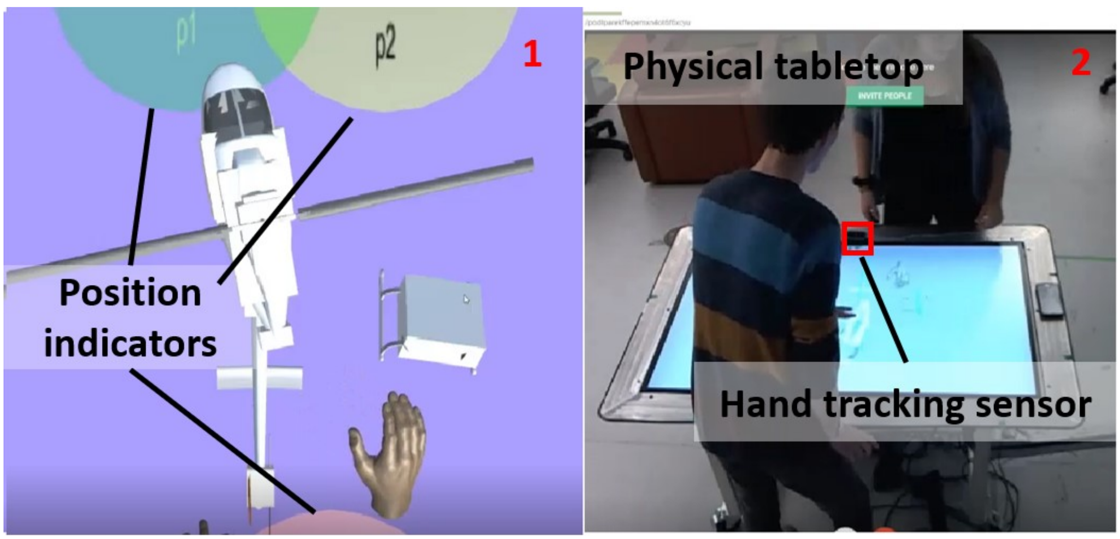

Figure 10: Hardware setup at the collocated location.

4.3. “Hover condition”: 3D models hover over the virtual tabletop

In this condition, remote collaborators wore an HMD to collaborate around a virtual tabletop inside the immersive virtual room. 3D models were presented over the virtual tabletop. We installed a hand tracking sensor in front of HMD to track user’s hands. Having the tracking sensor on the HMD let users see their hands in their actual positions. For example, if users kept their hands in front of their face, they would see virtual hands in front of their face. Remote collaborators interacted with the 3D model over the virtual tabletop directly with their virtual hands. Figure 11 (top) shows the remote collaborator during this condition.

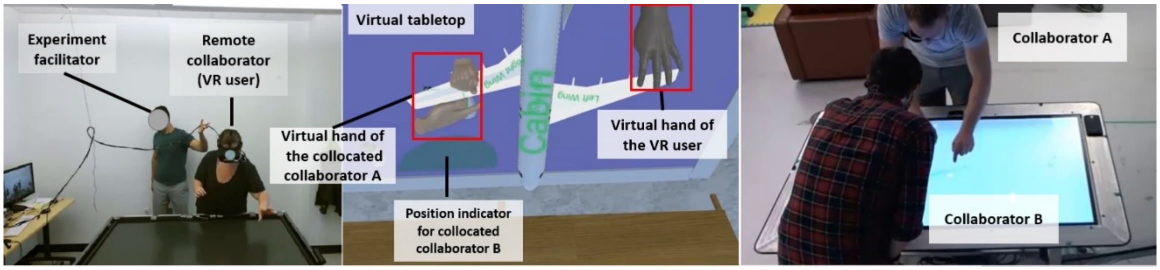

Figure 11: The Hover condition – Left: the remote participant. Middle: View of the remote participant during the Hover condition. Right: same time at the collocated location.

4.3.2 "Fishtank condition": Using HMD & 3D model within the virtual tabletop

In this condition, remote collaborators wore an HMD to collaborate around a virtual tabletop inside the immersive virtual room. 3D models were presented within the virtual tabletop. Remote collaborators had the exact field of view that collocated collaborators had around the physical tabletop, with the added benefit of a true 3D view of 3D objects, with depth and parallax. We calibrated the virtual hands to be seen on the tabletop, which means remote collaborators could see their virtual hands within the virtual tabletop. To create the illusion of a virtual tabletop and avoid conflict between the proxy table height and the illusion of reaching into the table, we levelled up the virtual tabletop, so when remote collaborators put their hand on the physical tabletop, they would see them within the virtual tabletop. This condition provided the parallax field of view that collocated collaborators have on the physical tabletop. They are able to see the virtual hands as a reflection of their real hands within the virtual tabletop.

Remote collaborators interacted with the 3D model directly with their virtual hands. Figure 12 (top) shows the view of the remote collaborator during this condition. Figure 13 shows the Fishtank and the Hover conditions side by side. 3D objects could not be moved outside of the table bounds in the Fishtank condition. Also, participants were prevented from placing a 3D object "within" the table or outside the XY bounds of the table in the Hover condition.

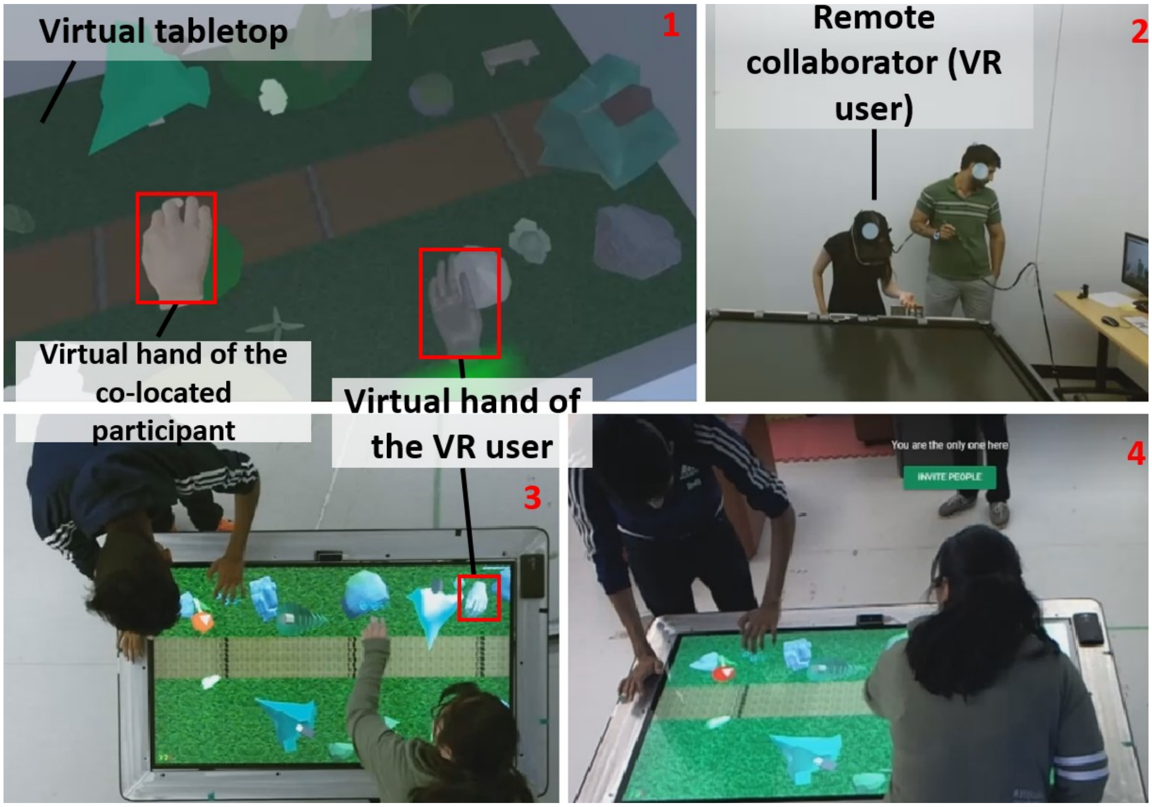

Figure 12:Fishtank condition – Top (1,2): View of the remote collaborator during the Fishtank condition. Bottom (3,4), same time at the collocated location.

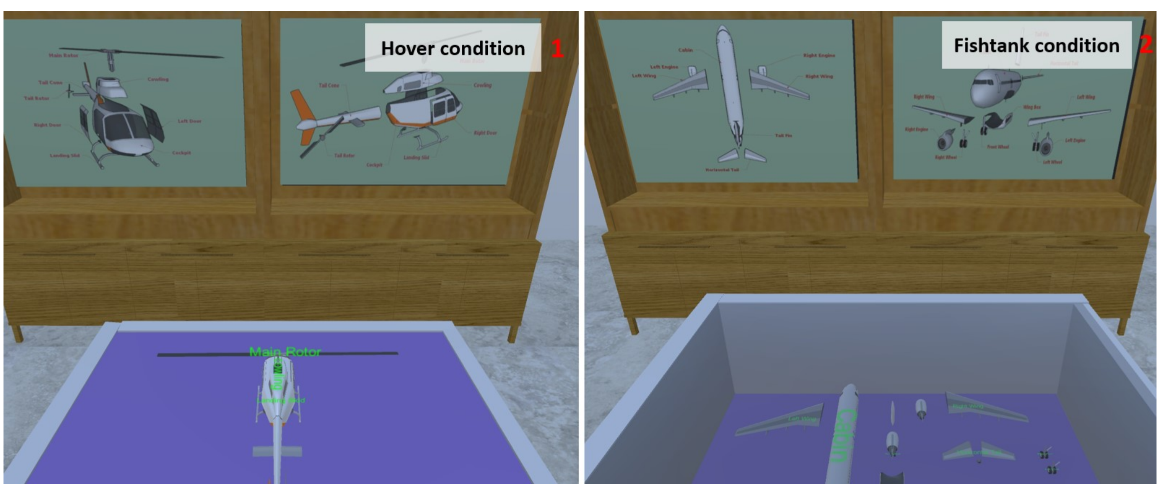

Figure 13: Left (1) Hover conditions,Right (2) Fishtank condition.

4.3.2.1 "Tabletop condition": Working on touch physical tabletop at the remote location

In this condition, the remote collaborator used a touchscreen tabletop instead of an HMD. This tabletop ran the same application as the tabletop in the collocated collaborators' location. Table 5 compares study conditions.

4.3.2.2 Selection of conditions

The first and second conditions (using the immersive virtual environment and virtual tabletop) allowed the remote collaborator to have a similar field of view to the collocated collaborators.

We also provided the model of the meeting room that the collocated collaborators worked in. This feature allowed remote collaborators to experience the same environment that the collocated collaborators experienced. The virtual room was very similar to the collocated location and was the same size. We included virtual models of the furniture at the collocated location and placed them at the same locations in the virtual environment. In the first design, we used a virtual cafe as a common place for the meeting; collocated participants could see the projected cafe around themselves and they knew that the remote person was in the same virtual café.

Our setup provided an asymmetric environment with similar cues for collaborators. We did not find a method that allows us to use an avatar on the physical tabletop. We did not have eye tracking system or face recognition sensors to match the person body language and face to their avatar especially remote person had an HMD on their faces (harder to track the eyes and face). Therefore, we used position indicators which played the same role as solid avatars. Position indicator showed the location of the counterpart collaborators relative to the physically-virtually mapped tabletop.

We used the virtually-physically mapped tabletop as the shared space. We did not remove the virtual tabletop in this condition because it acted as a reference point for the remote collaborators. For example, where collocated collaborators were standing relative to the tabletop. Using the virtual tabletop could help remote participants to have a similar field of view to collocated participants and build a spatial mental map that is more comparable to the physical collocated location. We believe having a condition without a virtual tabletop is worth exploring and it should be considered in future studies. The physical tabletop acted as a reference point for VR users, but at the same time, it limited the movement of participants. For example, sometimes a 3D object was on the opposite side of the virtual tabletop and participants could not reach the object by bending on the physical tabletop. Then the only way for a VR user to access the object was walking around the physical tabletop.

Table 5 conditions for the IMRCE study.

<table>
<tr><th></th><th>Collocated location</th><th>Remote location</th><th>Cues</th></tr>
<tr><td rowspan="4">Hover condition</td><td rowspan="11">- Using 3D hand embodiments to visualize remote collaborator hands on the physical tabletop.

- Visualizing location of remote collaborator on the physical tabletop by highlighted side indicators

- Using the touch tabletop to interact with 3D models</td><td>-Working with a 3D model over the virtual tabletop</td><td>-Position tracking at both collocated and remote location</td></tr>
<tr><td>-Interact directly with 3D models</td><td>-Hand tracking at both collocated and remote location</td></tr>
<tr><td>-virtual hands are over the virtual tabletop</td><td>-Verbal communications</td></tr>
<tr><td>-Using HMD</td><td></td></tr>
<tr><td rowspan="4">Fishtank condition</td><td>-Working with a 3D model inside the virtual tabletop</td><td>-Position tracking at both collocated and remote location</td></tr>
<tr><td>-Interact directly with 3D models</td><td>-Hand tracking at both collocated and remote location</td></tr>
<tr><td>-virtual hands are inside the virtual tabletop</td><td>-Verbal communications</td></tr>
<tr><td>-Using HMD</td><td></td></tr>
<tr><td rowspan="3">Tabletop condition</td><td>- Using 3D hand embodiments to visualize collocated collaborators' hands on the physical tabletop.</td><td>-Position tracking at both collocated and remote location</td></tr>
<tr><td>-Visualizing location of collocated collaborators on the physical tabletop by highlighted side indicators</td><td>-Hand tracking at both collocated and remote location</td></tr>
<tr><td>-Using the touch tabletop to interact with 3D models</td><td>-Verbal communications</td></tr>
</table>

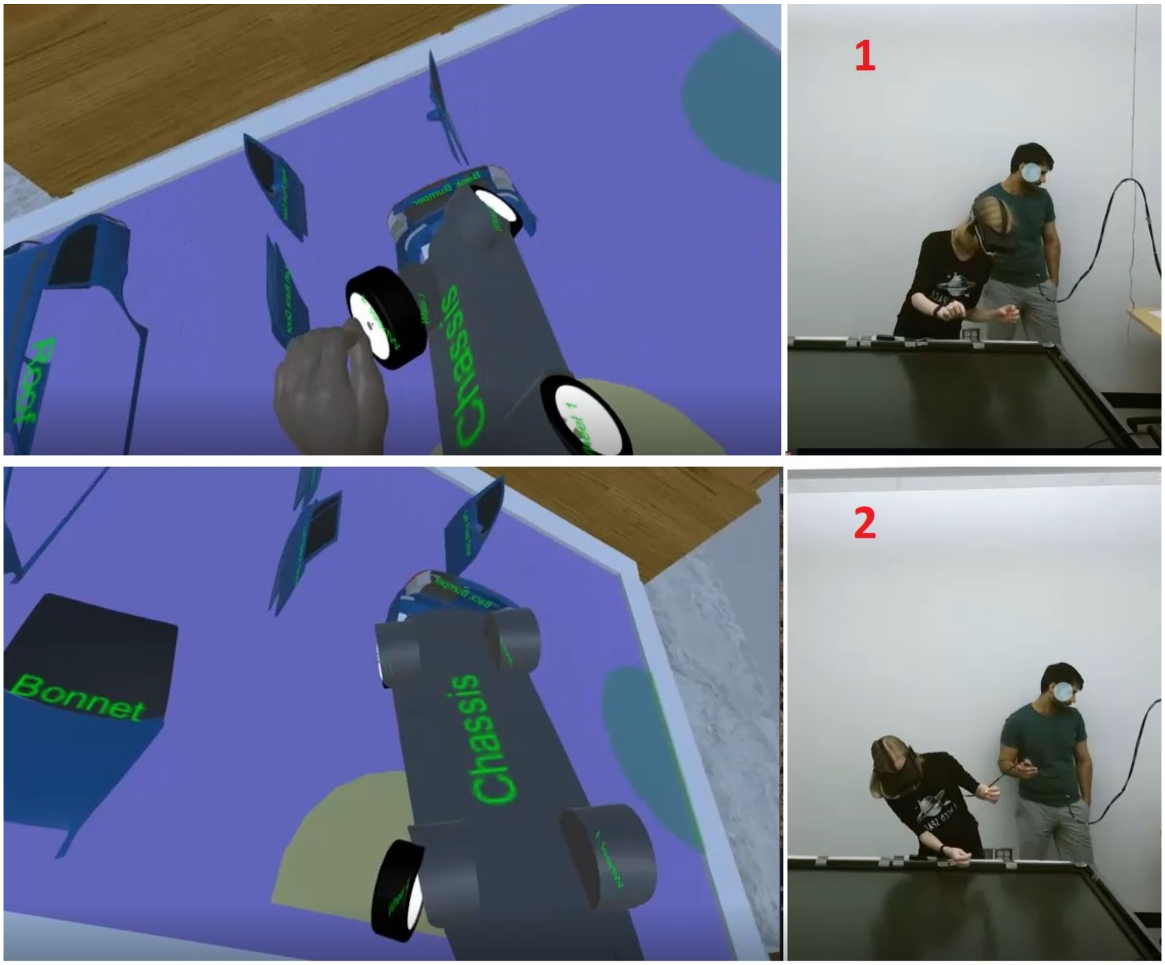

Figure 14: (1) Participant tilted her head to the right to check if the tire belonged to the right side of the chassis. After she saw that there is no spot, (2) she tilted her head to the left to attach the tire in its proper position. The participant did not rotate the chassis.

The third condition provided a non-immersive mode of mixed presence tabletop collaboration that is reminiscent of prior work. In a manner like VideoArms [81] and KinectArms [101], our system uses hand embodiments and indicators to show the location of collaborators relative to the tabletop. This condition involves a strictly symmetrical hardware/software setup for remote and collocated collaborators and allows us to compare this with the benefits of immersive embodiments and immersive 3D object views. We used this condition as a baseline to the VR conditions to explore the impact of using an immersive virtual environment on collaboration.

4.4 Tasks and Discussions

We designed three different types of task for the study. In all three task types collocated participants always saw remote collaborator’s hand embodiments and indicators that represent the remote participant's location on the tabletop. The remote participant also saw hand embodiments and indicators that show the place of collocated participants about the tabletop and the position of their hands when working with the 3D model. Figure 12 shows virtual hands belonging to a collocated participant inside the virtual environment. Figure 15 shows position indicators inside the virtual environment. In all conditions, a live audio link allowed participants to engage in verbal communication.

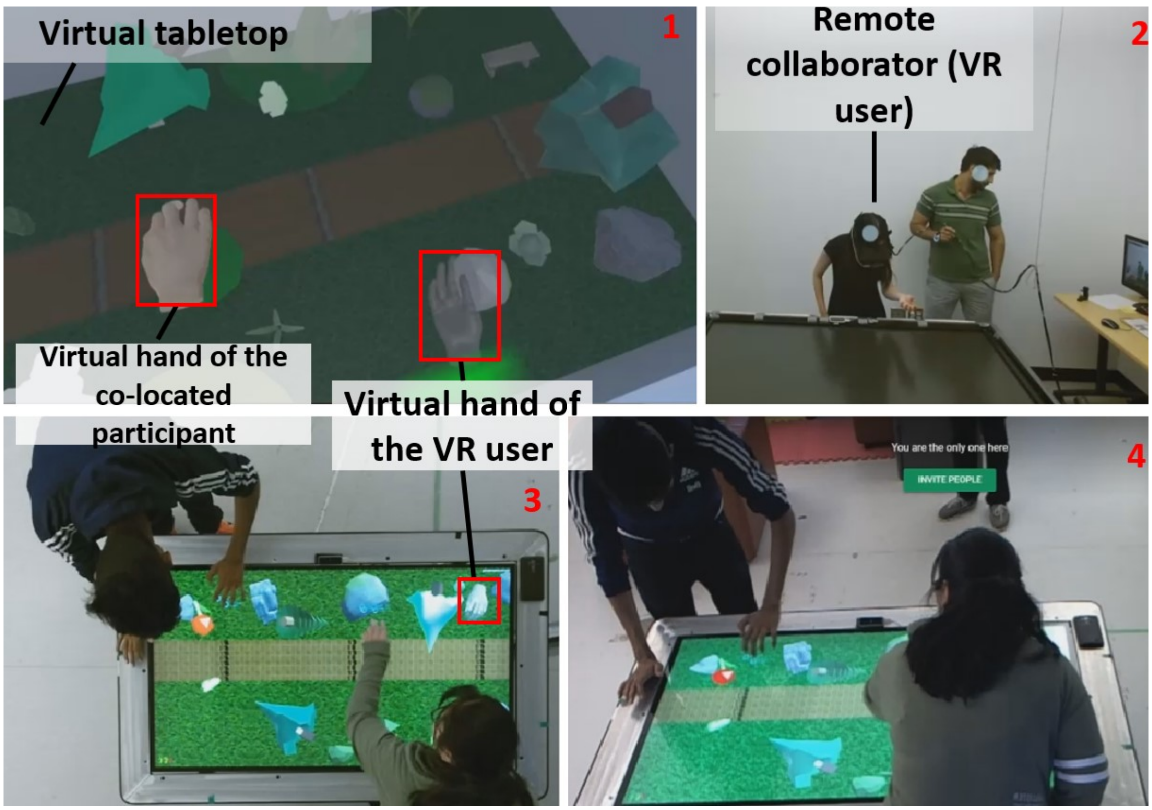

Figure 15: (Repeated figure) Fishtank condition – Top (1,2): View of the remote collaborator during the Fishtank condition. Bottom (3,4), same time at the collocated location.

The study’s within-subject design meant that each of the three collaborators experienced each of the three task types as a remote collaborator and a collocated collaborator;

therefore, we developed three unique but similar tasks for each task type. The task types are described in the next sections.

Assembling Tasks

We asked remote and collocated participants to work as a group. In this task, participants were asked to assemble a simple 3D model from its parts. Three models of similar
4.4.1 complexity were used for the three tasks of this type: a helicopter, a plane and a car. We provided two 2D maps for each model for the participants to help them complete the task. Participants were required to rotate the parts to look at them from different perspectives. We provided two large screens at the collocated place to display the instruction maps. We also provided the model of exact displays inside the virtual environment. Remote participants could look at virtual displays for checking the instruction maps. Figure 16 shows the model of the helicopter before and after assembling. Figure 17 shows an example of instruction map of a 3D model.

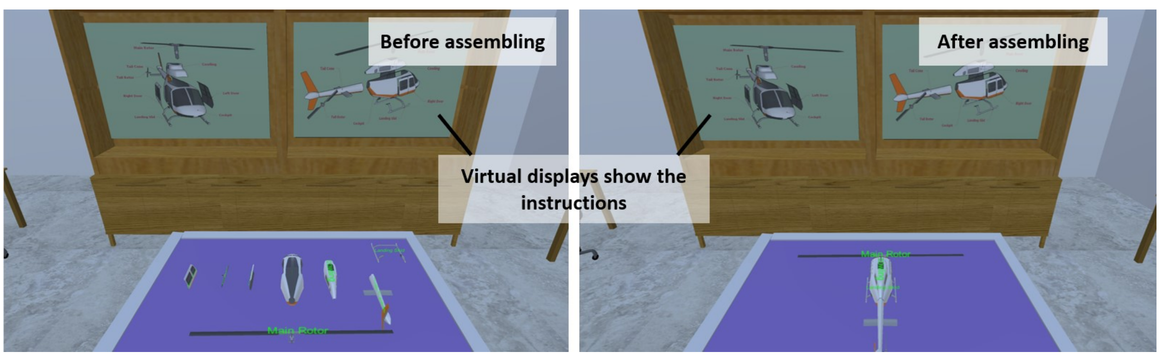

Figure 16: Participants need to build the complete 3D model from provided 3D parts.

For the Tabletop condition, remote participants had two 21-inch screens in front of them to look at the 2D maps for each model to help them complete the task. The physical tabletop at the remote location used the same application that we used for the collocated location.

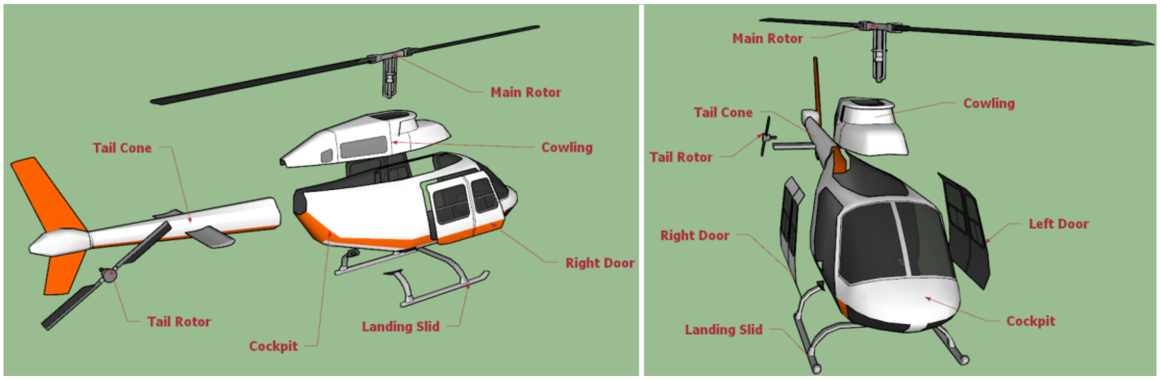

Figure 17: The instruction maps for assembling a 3D model.

The 3D model (or its parts) was shared and synchronized between participants. To complete the task successfully, participants had to cooperate with each other, pay attention to their group mates and be aware of their current activities to avoid interfering with each other's work. For example, a participant should not try to scale up a 3D object while the other participant was trying to move it at the same time. However, IMRCE did not allow two actions to occur simultaneously. In all three tasks, the system changed the colour of an object to bright yellow when it was selected by a participant to let other participants know that someone was interacting with that object.

4.4.2 Searching Tasks

The Searching task was a simple interactive game. We created three virtual scenes of similar visual complexity for the three tasks of this type, depicting a desert, a car racing stadium and a garden. We placed nine buttons of three colours on different sides of 3D objects. For example, we placed a red button under a rock, a yellow button on the bottom of a tree, a green button on the back side of a bench, etc. We assigned a colour to each participant and asked them to find the buttons of their colour and press them. After a participant pressed the button on an object, that object disappeared from the scene. Three indicators on the top corner of the screen showed the number of buttons that were pressed for each colour. We explained to participants that this game is not a competition and they could help each other, without providing examples of how they may help each other. Like in previous tasks, we used position indicators to show the location of participants and their virtual hands. Figure 18 shows the Searching task on the touch display and inside the virtual environment.

4.4.3 Illustration Tasks

For this task type, we created short videos that explained in plain language the functionality of three mechanical systems of similar complexity for the three tasks of this type. These systems were a car engine, a steam engine and a wind turbine. Each video was one-minute in length and it described each part of the model in plain language. We asked the remote participant to watch the video and then explain the system to the collocated participants using the 3D model of that system. Like the previous task, all participants could interact with the 3D models. We encouraged participants to talk and work with each other. For example, we explained to collocated participants that they could assist remote participants to manipulate 3D parts or ask remote participants for extra details. We told remote participants that they could ask collocated participants to help them demonstrate the functionality of the system. For example, we told them: “You can ask other participants to help you explain the parts.” Figure 19 shows an engine of a car as one of the Illustration tasks.

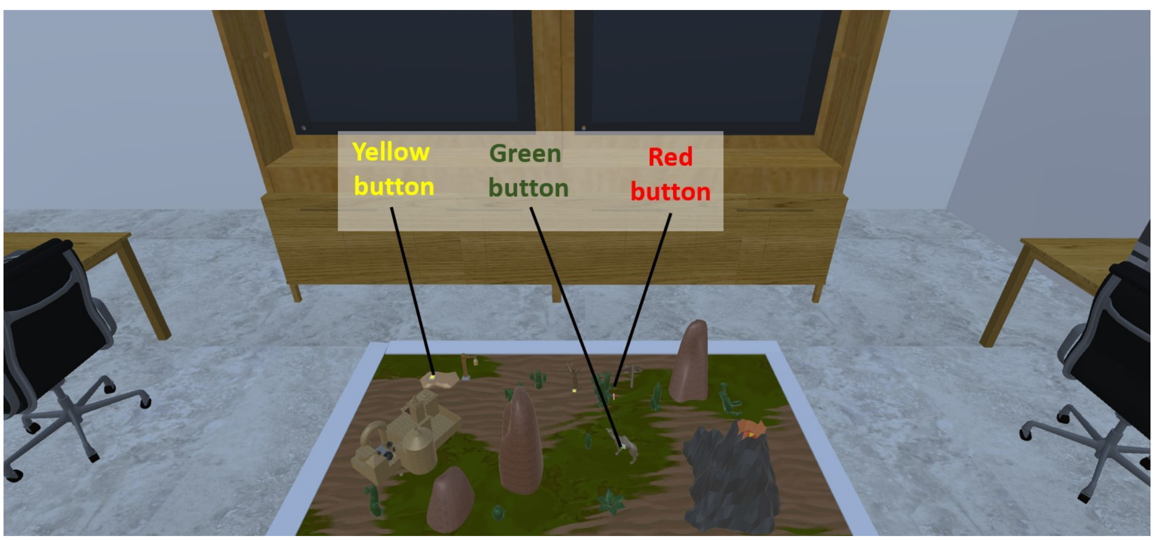

Figure 18: The Searching: Finding nine buttons and pressing them.

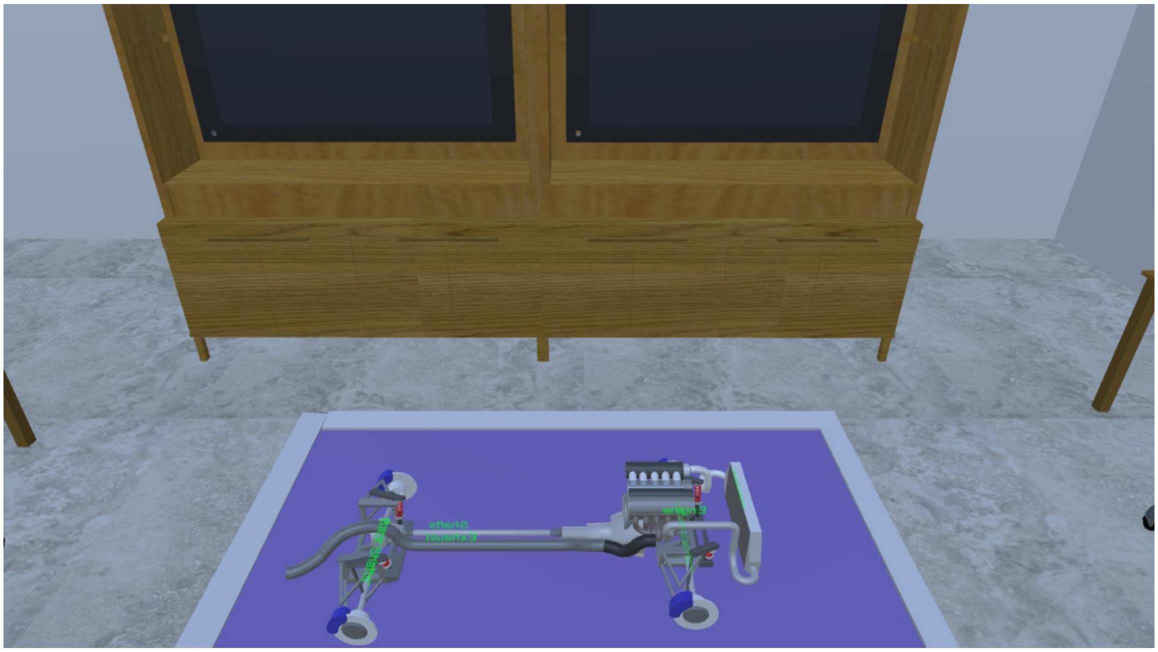

Figure 19: In this task, the remote participant is required to explain the workings of a simple engine after watching a short video.

Collocated participants were on the receiving end of the instruction. Therefore, the remote participant had to become aware of the status (i.e. if they understood their explanation) of listeners and explain the model to them. Collocated participants were required to answer their remote collaborator's questions to show that they learned how the system works. We did not provide the questions. However, we told remote participants in advanced that they should ask each of collocated collaborators (at least one question) to explain back the functionality of parts.

4.4.4 Training

We let participants become familiar with our application before we started the study. For training purposes, we provided a set of interactive 3D cubes on the physical touch tabletop and over the virtual tabletop. We asked participants to perform simple actions such as moving, scaling, rotating and ordering the objects to become familiar with the application.

All participants of each group had three training exercises: one on the touch physical tabletop at the beginning of the study, another one on the virtual tabletop (wearing HMD) before the Fishtank condition and the last one over the virtual tabletop (wearing HMD) before the Hover condition. Training was done individually and there was no group instruction. This training session helped the participants become adept at using our application.

4.4.5 Rationale for the Task Types

McGrath [156] states that generation and execution activities are the primary tasks in collaborative workspaces. He explains these activities tend to involve the creation of new objects, navigation between objects, and manipulation of existing artifacts (virtual and physical). Examples include activities such as “construction (page layout, diagram assembly), organization (arranging, ordering, or sorting artifacts), design (drawing, generating an outline), or exploration (finding specific types of artifacts in space).” He also notes that other tasks involve workspace awareness, citing decision making as an example.

Assembling task- The Assembling task is a proxy for collaborative activities that follow a united objective (assembling a model) and all participants help to achieve this goal. The Assembling task is a type of physical repair collaborative task. Physical repair collaborative tasks initiate conversation (encourage participants to collaborate), maintain awareness and develop a common ground that works for everyone [157]. An example is bicycle repair task [158]. In this bicycle repair task, one person uses tools to repair the bicycle, and another person provides guidance and instruction only. Kraut et al. [158] concluded that a “shared visual space is essential for collaborative repair because it facilitates situational awareness and conversational grounding” [157]. CoVId [159] is another example of the use of a physical repair collaborative task for evaluation. In the study, participants were asked to assemble a virtual 3D chair from its parts.

Searching task- The Searching task is a proxy for collaborative activities that follow a united objective (finding all the hidden items in a model here) and participants help each other to achieve the unified goal. However, each participant has a defined responsibility to follow (here it is finding specific coloured items). This task encourages participants to interact with 3D models but because everybody works on the 3D models at the same time, participants are driven to pay attention to the other participants (their positions, hands) and their activities to maintain their group awareness and avoid conflicts and interrupting other participants actions.

The Assembly and Searching tasks are one form of a compound coordination problem that Clark [160] Malon et al. [161] and Malon [156] described: "A participant is to provide useful instruction for others to identify what help they need, who needs the help, when to provide assistance, how to deliver the message to other participants, and whether they understand the message or not. Assistance must simultaneously coordinate with others and with their actions and the current state of the task [156]." Both the Assembly task and the Searching task have the elements of organization, exploration and navigation.

Illustration task- The Illustration task is a proxy for activities that are focused on presentation and demonstration (here it is describing the functionality of a model). In demonstration and presentation activities, one side is leading the session and answering the questions and the other usually follows the presentation and asks questions. Regenbrecht's work [162] is an example which designed an augmented virtual presence system for remote collaboration. They used a 3D virtual environment (an office room) as the participants' meeting location. Their system integrated 2D data into the 3D model (to clarify: a meeting room is a 3D world, but the projector projected 2D information on the wall). For the study, they used an illustration task in which 3D models of several cars were presented and participants discussed and decided on which was the most aesthetically pleasing. The illustration task has the elements of exploration and navigation.

4.4. Counterbalancing

We recruited 18 groups of three participants to have all permutations of three conditions. Participants could naturally get better at doing the same task more than once. Therefore, their cognitive and social behaviours for the repainting tasks could be different from participants who were not doing that task for the first time. To minimize learning effect, we are using nine tasks (3 of each of three task types). Appendix E shows counterbalancing the order of performing tasks and conditions.

4.5 General Study Design

4.5.1 Procedure

We recruited 18 groups of three participants, with the age range of 18-54, 30 participants identified themselves as men, and 24 participants identified themselves as women. The collocated location was a meeting room with the size of 24x19 feet; the remote location was a room of 10x12 feet. We used a full HD 55” physical tabletop at the collocated location and a 62” HD physical tabletop at the remote location. Remote participants used an Oculus Rift HMD which was running on a gaming desktop computer (Core i7, 3.4 GHz, Nvidia GTX1070). We used the Unity game engine to develop the touch application and the immersive environment. We used the open source (OSC) library and Unet (Unity network) for communication between the touch application and immersive environment. We used Leap motion sensors for hand tracking and the DT-DT [163] position tracking system to track collaborator locations.

We rotated people between the tasks and in each of the three of conditions. One of our researchers was at the collocated site to coordinate the study. The two collocated participants were informed if the remote person was using an HMD to connect to the room through an immersive virtual environment or if the remote person was using a physical tabletop. We explained to participants that we were tracking their hands and positions and visualized them at the counterpart location. We explained to participates to what range hand tracking and position tracking sensors can track their hands/positions.

4.5.2 Data collection

Our system logged information such as the location of participants and the position of their hands. We limited each task to a maximum of five minutes. If a task went over five minutes, we stopped participants from continuing the task. In addition to logging the system and videotaping both collocated and remote location activities, we screen-captured activities inside the virtual world and on the physical tabletop. Participants filled in background questionnaires and postconditions questionnaires. We asked participants to consider all three conditions while answering the questions.

Participants signed an online consent form and filled in an online background questionnaire that asked them about their previous experience using collaborative software, 3D models, and HMD before coming to our lab for the actual study. This information helped us to have a better understanding of our participants' knowledge and possible earlier experiences in using MR collaborative environments.

After having all three participants in our lab, we asked them to sit with us for few minutes. We introduced ourselves and the lab. Then we asked participants to introduce themselves. The primary purpose of the pre-study meeting was for breaking the ice between collaborators and helping them to become more comfortable with each other. We also had groups of participants that were friends. Note, in our recruitment notice, we encouraged people to join us as a team of three. We had the pre-study meeting for all groups regardless of their relationships.

We introduced three gestures (moving, rotating and scaling). We asked participants to try the gestures on the touch physical tabletop. After training participants around the physical tabletop, we asked them to follow us to another room that was used as the remote location. We installed a physical tabletop and HMD in the remote room. We gave a brief description of how to use the HMD and interact with 3D objects inside the immersive environment. Each participant wore the HMD and followed the training instructions that were given to them. All participants experienced the same training.

We also showed participants the position and hand tracking hardware with a simple explanation of their functionality. After the training session, we started the actual study.

We had a thoroughly counterbalanced study, and all participants experienced all three conditions and all three task types (in different conditions). Table 6 shows the counterbalanced order of performing tasks and conditions between participants. We followed the counterbalanced table for participants, tasks, and conditions.

Table 6: The counterbalanced order of performing tasks and conditions between participants.

Conditions	Task	Participants	Participants
First Condition	Task 1	P1, P2	P3
	Task 2	P1, P3	P2
	Task 3	P2, P3	P1
Second Condition	Task 1	P1, P3	P2
	Task 2	P2, P3	P1
	Task 3	P1, P2	P3
Third Condition	Task 1	P2, P3	P1
	Task 2	P1, P2	P3
	Task 3	P1, P3	P2

As we mentioned earlier, at the end of each condition, participants filled in a questionnaire (Likert scale) asking them to rate their experience during the collaboration. We specifically asked participants about their collaboration experience with other participants and their experience with the system that was designed for collaboration by using the IRMCE toolkit. Answering post-task questionnaires provided data related to these categories:

- The mutual understanding between collocated and remote participants.
- General collaboration experience with the collocated/remote participants.
- Experience in working with other participants and assembling the 3D models from their parts.
- Experience in working with other participants and finding the buttons on different sides of the 3D objects.
- Experience in working with other participants and explaining the model.
- The time that participants paid less attention to other participants regarding their physical absence.
- Experience of being excluded by the collocated/remote participant.
- Experience with having the position of the collocated/remote participant at the counterpart station.
- The relation of position indicator and 3D virtual hands with increasing group awareness.

At the end of the study, we asked participants to sit with us in a group to talk about their experience (semi-structured group interview). We started by asking participants about their experience and feelings about each condition. We encouraged participants to talk about the reasons for their comments. We asked participants if they found the positions tracking and hand tracking useful and if they could give us specific examples of this. We continued with asking about collaboration relationships and if they had any moments that they felt excluded or less informed about ongoing actions. We discussed the tasks with participants. We asked participants for what type of activities they prefer an immersive virtual reality or a touch display. The interview took between 10 – 15 minutes for each group. Appendix B shows that post condition questionnaires and post study interview questions

We asked participants about the use of physical tabletop when they were using immersive virtual environment and if they found it useful in term of a physical reference and physical feedback (we calibrated the virtual tabletop to be aligned with the physical tabletop at the remote location). At the end of the interview, we asked participants to give us any suggestions and feedback they had. We recorded and transcribed these interviews.

We wanted to capture the interactions with the 3D model (e.g., rotating, scaling and exploring the shared data) but also to look for more subtle cues that people make when sharing information and collaborating with each other. We looked for evidence that showed how both collocated, and remote participants managed to work on 3D models.

4.6 Analysis Methods

As explained in section 2.7 of chapter 2, we evaluated awareness and presence in six categories. We conducted a mixed methods study, and our data analysis is a mix of qualitative and quantitative analysis.

We video coded the captured videos three times and transcribed all the interviews and conversations. NVivo software was the primary tool to perform the data analytics. We watched all the captured videos from both the collocated and remote location separately for the first round of video coding. For the second and third rounds, we watched the corresponding videos of the remote and collocated location at the same time.

We used five Likert scale questions for the postconditions questionnaires and report the results in percentages. For example, we asked if participants were satisfied with the hand tracking system, meaning that if 20/50 participant picked somewhat "agree," and 10/50 picked "strongly agree," then we report that 60% of participants were satisfied. We also report the results of running a statistical test on postconditions questionnaire data after giving weight to each category (1 for strongly disagree, 2 for somewhat disagree, 3 for neutral, 4 for somewhat agree and 5 for strongly agree) [164].

Our system recorded a log from each participant's activities such as hand gesturing, scaling (tabletop app) and rotating (tabletop app). Also, we logged information such as the location of participants and the position of hands (Leap sensors). We timed each task. Note, we limited each task to maximum five minutes and participants were not permitted to continue the task after the five minutes.

For analysing the results of coded video data, we used the Mauchly test to examine the sphericity of data. If the assumption of sphericity was not violated, then we used one-way ANOVA with repeated measures test and post-hoc comparisons using the LSD. If the assumption was violated, then we used Greenhouse-Geisser estimates of sphericity to correct the degree of freedom. To compare two groups between only two conditions, we used the paired sample t-test.

For analyzing the postcondition questionnaire, we used Wilcoxon ranked sign test to compare the two conditions with each other and Chi-square test to compare the three conditions to each other. Note that we ran a normality test on the results of the
4.7 questionnaire. Since the data were not normal, we used a non-parametric test for analyzing questionnaire data.

Background Questionnaire

The background questionnaire showed that 92% of participants frequently worked in groups, and 64% of participants indicated that they regularly work with remote collaborators within their groups. 57% of participants had previous experience with the 3D model software, and 64% of participants had tried an HMD at least once before. 87% of participants rated themselves as skillful in collaboration activities. The demographics questionnaire shows that our study population is familiar with group collaboration and more than half of them collaborate with remote collaborators on a regular basis. More than half of the participants had previously experienced VR and working with 3D models which shows that use of VR is growing in daily life activities.

Table 7: Summary of the results of the background Questionnaire.

Worked in groups		92%	
Groups including a stranger		~67%	
Group composed entirely of strangers		50%	
Regularly work with remote		64%	
Working with 3D software		57%	
Used HMD		64%	
Skillful in collaboration activities (self-assessment)		87%	
		Collocated collaborators	Remote collaborators
Paying attention to	Position of	74%	37%
	Body language of	77%	39%
	Actions of	80%	57%

74% of participants said that they pay attention to the position of their partners while they are in the same location as them but only 37% participants are aware of the position of other collaborators while they are in different locations (when they were using video conferencing). 77% of participants pay attention to the body language of their collocated collaborators. But only 39% of participants could follow the body language of remote collaborators (when they were using video conferencing). 80% of participants indicated that they were aware of their collocated collaborators' actions (sharing, manipulating, editing) while 57% of participants were aware of a remote collaborator's actions. The demographics questionnaire shows that more than 70% of collocated collaborators observed their partner's position, body language and collaborators' actions to increase their awareness and maintain their collaboration activities. In three groups, all three participants were friends with each other; in six groups, two of the participants were friends with each other. In the final nine groups, all participants were strangers.

4.8 Results

4.8.1 Task Performance and Distribution

We consider task performance and distribution metrics between interface conditions for the Assembly task type, and task performance for Search tasks (as each collaborator had their own 3 buttons to press, we do not assess task distribution for Search). The Illustration tasks were open-ended and role-based, so we do not report a task performance or task distribution metric.

For Assembly tasks, we used the performance metric:

(PARTS_ASSEMBLED / TOTAL_PARTS) / TIME_TAKEN

where TIME_TAKEN is 5 minutes for incomplete tasks and as measured for abandoned and completed tasks, and TOTAL_PARTS is the number of parts in the specific model used. While there is an effect of Interface approaching significance at $p=0.05$, $F(2, 104) = 3.829$, $p = 0.056$, post hoc tests did not show significant pairwise differences between Interface conditions.

We consider task distribution as the ratio of parts assembled by the remote collaborator to those assembled by the collocated pair. We found a significant effect of Interface on the ratio of assembled parts between the collocated and remote locations, $F(2, 51) = 13.658$, $p< 10^{-7}$. Collocated participants assembled more parts during the Tabletop condition ($M = 0.7$, $SD = 0.058$) in comparison to remote participants ($M = 0.3$, $SD = 0.058$).

For the Search tasks the performance metric was BUTTONS_PRESSED/TIME_TAKEN, where TIME_TAKEN is as previously defined (in each task there were 9 buttons, so we did not use total buttons in the metric). We found no significant effect of interface $F(2, 104) = 0.272$, $p = 0.762$. We then considered the difference in time taken for the remote collaborator to press their buttons vs. the average time taken for the collocated collaborators. We found no significant main effect of Interface on time difference between collocated and remote participants, F (2, 52) = 0.718, p = 0.493.

4.8.2 Interacting with 3D Objects

We counted the number of interactions that participants had with 3D objects at both remote and collocated locations. There was a significant effect of interface on the number of interactions of remote participants with 3D items during the Illustration task F (2, 34) = 7.989, p= 0.002. Remote collaborators interacted more when using Hover (M = 65.842, SD = 10.96) or Fishtank (M = 63, SD = 27.209) compared to Tabletop (M = 33.631, SD = 25.219), while collocated collaborators had more interactions with the model in Tabletop (M = 33.684, SD 2.731) than in Hover (M = 14.579, SD = 0.983) or Fishtank (M = 11.158, SD = 1.356).

In the post-condition questionnaire, we asked participants if they were satisfied while interacting with shared 3D objects in relation to working with other participants. As expected, collocated participant responses were consistent across interface conditions (ranging between 66-70%). Remote participant responses varied by condition: 59% were satisfied in Hover condition (M = 3.7, SD = 1.075), 43% in Fishtank (M = 3.11, SD = 1.208), and 33% in Tabletop (M = 2.98, SD = 1.107). This difference was significant: χ^2 (1, N = 54) = 13.629, p = 0.001.

During the group interview, many participants expressed that the interaction dynamics and the field of view for manipulating 3D objects were more natural in Hover. For example, P1 stated: *"I preferred [Hover] because I thought it was easier to manipulate the objects, grab them and take hold of them and rotate them.*" P2 stated: *"...pick it up, look at the bottom, leave it there, press the button, then grab something else—that was very natural."* P39 mentioned: "*when it's right in front of you it's easier to reach out and grab*." P50 said: "*I had a good perception of what was going on...*". Reasons expressed for liking Fishtank include the birds eye view and the ease of reaching for objects. P8 explained: "*I liked Looking into the box* [Fishtank]*.... I felt like that I can reach in and do things."* P2 explained*: "I found that reaching down, that seemed easier."* A minority of participants (5) expressed a preference for tabletop when remote, feeling the interaction was easier or more direct. P23: "*It is easier to handle and pick up objects on tabletop compared to VR."*, P13 said: "*[in Tabletop] you are interacting with the object itself. For the VR you know it is not there. It's hard to put your mind into 'Okay, I'm grabbing that.'*"

Looking at the observation notes and coded video data we identified behaviours common to participants working on a task (Hover or Fishtank). For example, VR users during the Hover condition combined rotation and translation with moving their body (tilting their heads and/or torso, bending) and changing their position around the tabletop. Participants moved the objects inside the VE to perform actions that helped them complete a task, for example, bringing an object closer to themselves for easier access, or move other objects out of their sight to have more space for working. We observed that some participants brought the 3D parts closer to their face in a VE (Hover condition) to investigate the 3D objects. During the Fishtank condition, participants still used body movement such as tilting their head and moving their positions; however, it was less effective for participants since they could not bring the objects close to their face (we saw some participants bring their face close to the objects within the virtual tabletop).

4.8.3 Hand Embodiments and Position Indicators

4.8.3.1 Hand Embodiments

84% of participants agreed that seeing the virtual hands of the counterpart participant(s) increased mutual awareness. There was no effect of interface on the participants perception of finding hand embodiments useful at remote χ^2 (1, N = 54) = 2.893, p = 0.235 or collocated χ^2 (1, N = 54) = 5.328, p = 0.07 locations.

As expected, hand embodiments generally enhanced awareness during collaboration. In the interview's participants indicated that seeing the virtual hands of other participants helped them to be more informed about their counterpart collaborators' actions and what they were working on, and useful to locate collaborators around the table. *P25 mentioned: "[hands] could help to understand. It is like watching a video of the lecture and being there."* P17 said: “*If I saw that the remote person was grabbing or touching something then I would move my hands to something else so that both of us were not trying to do the same thing.”*

4.8.3.2 Position Indicators

76% of participants overall agreed that position indicators helped them to increase their awareness relative to their counterpart participant(s), in line with prior work. There was a significant effect of Interface on collocated collaborators’ sense that position indicators helped them to increase their awareness of the remote collaborator χ^2 (1, N = 54) = 14.235, p = 0.001. Participants found it more informative to know the position of the remote participants around the virtual tabletop during the Hover (M = 4.185, SD = 0.891) and Fishtank (M = 4.2688, SD = 0.8787) conditions in comparison to the Tabletop condition (M = 3.694, SD = 1.038). There was also a corresponding but less pronounced difference for the remote collaborator experience χ^2 (1, N = 54) = 7.903, p = 0.019, with position indicators found most useful on average in Fishtank (M = 4.138, SD = 0.997), followed by Hover (M = 4.083, SD = 0.960), then Tabletop (M = 3.759, SD = 1.053).

In the interview many participants gave positive comments about the position indicators. *That helps you a lot better. You know you should be looking for.”* P45 explained: “*Like the button one especially like I would point to something, and I would say OK well you know [p46]'s over here. So, you know maybe I can bring it over.*” P50 mentioned: “*It was useful because at least you know they are in the vicinity like you know they are going to move objects in front of them.*” *P39 said: “It's. Nice to know where people are so you feel included. In like in the experience.”* P30 said: “*I can see there is another person there. So, it sorts of makes you feel like the other person is present with you.”*

Some participants felt hand embodiments were sufficient. P18 said: “*I think hands are more useful than the positions. If the hand is already there, I already know what they are doing remotely. It doesn't matter where they are.”* P51 expressed: *“I just knew where they are from where their hands were.”*

4.8.4 Communication and Coordination

We counted the number of times participants-initiated discussion with the collaborator(s) at the other site in the Assembly and Search tasks. There was a significant effect of Interface on the number of times collocated collaborators-initiated conversations $F(2, 34) = 18.265$, $p<10^{-7}$, with more occurrences in Hover ($M = 5.06$, $SD = 1.924$) and Fishtank ($M = 4.11$, $SD = 2.026$) than in Tabletop ($M = 2.28$, $SD = 0.895$). There was less pronounced effect of Interface for remote collaborators as well, $F(2, 34) = 4.289$, $p= 0.022$, with more occurrences on average in Hover ($M = 3.28$, $SD = 2.396$), followed by Fishtank ($M = 2.67$, $SD = 1.283$), then Tabletop ($M = 2.17$, $SD = 1.339$).

We counted the number of times that participants received help from participants at the counterpart location. We considered these actions as helping: performing an RTS activity on a virtual object on behalf of their counterpart collaborator(s) (with or without their request), pointing out a location of an item (for example buttons), reporting the position of themselves or other participants around the tabletop (with or without a request), reading the labels of items (during Assembly task) for the counterpart collaborators. We found a significant difference for the number of instances of help received from remote participants $F(2, 34)$ 41.505, $p<10^{-7}$. Collocated participants received more help during the Hover ($M = 10.33$, $SD= 5.971$) and Fishtank ($M = 9.00$, $SD = 4.229$) conditions in comparison to Tabletop condition ($M = 2.5$, $SD = 2.036$). There was no significant difference between the condition at the remote location, $F(2, 34) = 2.429$, $p = 0.103$.

After the final condition participants were asked to rate the effectiveness of the last interface condition in relation to the previous two in terms of promoting mutual understanding and facilitating communication for each Task Type. We found no significant effect of interface on these ratings for the collocated experience. For remote collaboration, only 39% participants found Hover ($M = 3$, $SD = 097$) to be effective for communication during Assembly tasks when compared to the other techniques (67% for Fishtank [$M = 3.78$, $SD = 1.114$], 67% for Tabletop [$M = 3.72$, $SD = 0.895$]). This difference was significant $\chi^2 (1, N = 54) = 8.481$, $p = 0.014$. No other significant differences were found.

During the group interviews, comments about communication and coordination were varied, and not generally tied to specific interface conditions.

Table 8 shows show the results of postcondition questionnaires for communication and coordination.

Table 8: Participants answers in relation to their counterparts. Numbers are rounded. RE: Remote, CO: Collocated.

Interface	Hover		Fishtank		Tabletop	
Location	Co	Re	Co	Re	Co	Re
Mutual understanding	89%	83%	89%	67%	83%	83%
Over all communication	67%	83%	72%	72%	67%	72%
Communicating during Assembly	72%	39%	67%	67%	72%	67%
Communicating during Searching	89%	83%	78%	56%	89%	72%
Communicating during Illustration	67%	61%	61%	50%	78%	72%

During the group interviews, we had comments about communication and coordination that were not generally tied to specific interface conditions. For example, *"we planned what to do and worked out [details]"—P8.* P19 said: *"when we were trying to manipulate something, it is easier when you can say, 'Hey, can you pick that up for me I cannot reach it.'"* On coordination between sites, P15 said: *"The communication issues were just like we were not necessarily sure of the orientation of something."*

4.8.5 Exclusion

We asked participants for their level of agreement with the statement "There was a time I felt excluded by the collaborator(s) at the other location." Collocated and remote agreement was high for each of Hover (85.19%, 81.48%), Fishtank (81.48%, 85.19%) and Tabletop conditions (70.37%, 75.93%). We find a significant effect of Interface for the collocated experience χ^2 (1, N = 54) = 8.62, p = 0.013.Post hoc tests indicate more agreement for Hover (M = 4.37, SD = 1.087) compared to Tabletop (M = 3.83, SD = 1.225), with Fishtank close to Hover (M = 4.20, SD = 1.053). No significant differences were found for the remote location.

We asked participants for their level of agreement with the statement "There was a time I paid less attention to the other collaborator(s) due to their physical absence." Level of agreement for collocated and remote participants varied in the Hover (42.22%, 64.81%), Fishtank (77.78%, 72.22%) and Tabletop conditions (55.56%, 64.81%). A significant effect of Interface was found for the collocated experience χ^2 (1, N = 54) = 6.744, p = 0.034, with a higher agreement for Fishtank (M = 4, SD = 1.133) compared to Tabletop (M = 3.43, SD = 1.354), but not Hover (M = 3.87, SD = 1.15).

While collocated and remote participants self-reported periods of exclusion during the study, the general consensus during group interviews was that system features helped create a sense of co-presence. *P15 said: "You could that sense of presence and you think to like being with him… I know if someone is standing in front of me I coordinate according to his left and right it is going to be much easier.*" P49 explained: *"*I can see there is another present there and that makes me feel like the other person present with me.*"*

Appendix D show the results of postcondition questionnaires in details.

4.9 Discussion

In this study we examined the impact of an asymmetric mixed presence collaborative setup for tasks involving 3D objects. The intuitive value driving the research was that remote collaborators, lacking the benefits of collocation, could enhance collaboration by using an immersive interface suited to 3D object viewing and manipulation.

Our results provide evidence that this is the case. When remote, participants significantly preferred using the VR interfaces over the tabletop interface. While we find no difference of Interface in overall task performance for Assembly and Search tasks, Interface impacted distribution of work in the Assembly tasks: the remote collaborator assembled less in the symmetric tabletop condition than their collocated counterparts, but there was a more equal distribution in the VR conditions. In addition, while we do not see a significant increase in 3D object manipulations by the remote collaborator in the VR conditions for Assembly and Search tasks, there were significantly more in VR for the Illustration tasks, suggesting a more fluid engagement with the 3D model when describing its operation. P14 said: "*For* *me explaining a process of how a turbine works [Illustration task] was easy to explain it in VR. However, if the model was presented as a 3D model in a 2D [screen], it was really hard to explain how it works because you and your group member don't see it in 3D. So, for me like explaining things in the 3D way was easier."*

Interestingly, the position embodiments were viewed as most useful in the asymmetric VR conditions vs the symmetric Tabletop condition. It may be that in VR the remote collaborator was viewed as a more active participant and collaborator, and so collocated participants paid more attention to the position indicator. This is further supported by the increase in discussions initiated across locations, and the increase in number of times the remote participant assisted collocated collaborators.

The VR interface may place the remote participant in a "specialist" role, where they become more responsible for certain 3D operations, yielding both benefits and drawbacks. In the VR conditions the remote participant had access to perspectives that the collated collaborators did not, for example, the VR user could grab a 3D object and bringing to the eye level and rotate it like a physical object. Some participants, like P49 expressed that they liked being in a position to help: "*I liked we have the VR [Hover] for the airplane. Because I know the view is a little off for you guys. I was able to flip the plane easier to put the wheels on*". Coordination of action could suffer in the VR configurations, however: participants felt excluded significantly more often as collocated collaborators during the VR conditions than in the Tabletop condition. As P29 explained: *"when we were putting the car pieces together, I felt a little bit lost. Like I am excluded, and I am out of the loop"*.

The tabletop interface we used constrained translation to the X-Y plane of the table surface, while the VR conditions permitted translation in Z. This was a design decision made after pilot testing, intended to simplify tabletop interactions. While raised/lowered objects could still be selected by tabletop users, they would need to coordinate with the remote collaborator to connect parts in the Assembly tasks if the parts were far away in Z. We acknowledge that this further specialized the role of the remote collaborator in the VR conditions during Assembly tasks. As p22 said: *"The two people at the table can just maybe* *rotate and move things around. And then the third person [inVR] is able to kind of like place stuff together and kind of get the entire view*".

4.9.1 Strict vs. Relaxed WYSIWIS

Our results suggest that the relaxed WYSIWIS VR interfaces encouraged participation from the remote collaborator more so than the strict WYSIWIS tabletop configuration. The physical tabletop provides haptic feedback, it is a more familiar interface, and there are many touch-based RTS applications in regular use. Meanwhile, the in-air gestural interface in the VR conditions provided no haptic feedback, is less familiar, and could lead to arm fatigue. Participants could freely walk around the physical tabletop, while participants were more cautious and less comfortable walking around while wearing an HMD. Using an HMD might also cause dizziness or motion sickness.

When using Hover participants combined rotation and translation with moving their body (tilting their heads and/or torso, bending) and changing their position around the tabletop. Participants moved the objects around the virtual environment to perform actions that helped them complete a task, for example, bringing an object closer to themselves for easier access, or moving other objects further away to have more space for working. Some participants brought objects closer to their face for inspection. When using Fishtank participants still used body movement such as tilting their head and moving their position, but the work area was more constrained, and objects could not be brought close to their face (although some participants brought their face close to the objects within the virtual tabletop). We did not find pronounced differences between Hover and Fishtank in our measures, indicating that for the kinds of tasks we studied a more relaxed WYSIWIS configuration is very possible.

4.9.2 Mutual Awareness and Co-Presence

Our findings suggest that the VR conditions enhanced awareness and co-presence over the symmetric tabletop condition. Participants initiated significantly more conversation while working on VR conditions. Participants found hand embodiments and position indicators more useful from the collocated perspective when the remote collaborator was in VR, suggesting a higher level of engagement. In VR, the hand embodiments of collocated collaborators were rendered in 3D, and this may have encouraged a more visceral sense of co presence. P16 explained: "*When you see someone, you get that sense of presence and you want to communicate with them.*" P53 explained: "*With the headset, the communication was pretty good, you could also see where other people are and what they do*."

In Assembly tasks, the ratio of assembled parts shows that collocated and remote participants both contributed to the activity while using VR conditions; however, during the Tabletop condition the contribution of the remote participant significantly dropped. P9 said: "*Assembling was difficult for me because both of us were using the tabletop.*" While this can be explained by the change in interaction affordance previously described, there is some indication that using the Tabletop decreased awareness. P52 explained: "*I could not see it clearly, so I didn't make any contribution to combine the model [assembling]*."

4.9.2.1 Presence and Co-presence

Witmer and Singer [47] explain presence in an immersive environment as "a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences" [47].

Schubert [48] argued that there are two connected factors involved in the emergence of presence: construction of a mental model and attention allocation, and to be fully present a person should be aware of possible action patterns and the attention allocation that they require. The need for awareness in a collaborative VE extend to information related to action and attention (for example, seeing the other collaborator's hand gestures and position, or the location of other collaborators mapped to the VE). Each person should be aware of the status of the group such as who is talking, who is working on a specific document, what the current discussion is about and what their responsibility is.

There are some interesting indications that presence and co-presence reinforced each other in the configuration we studied.

Participants self-reported that seeing the virtual hands of their counterpart collaborators during the VR conditions increased their awareness and it was more informative in comparison to the Tabletop condition. P34 expressed: *"When we were using tabletop at the remote place, I think we mostly spoke through everything we really didn't point"*. P40 explained: "With working with other people without VR [Tabletop], I don't think it is necessary to have hands."

Multiple participants mentioned that being in a virtual facsimile of the collocated site increased co-presence. P16 said, "*It's nice to have like at least something to feel like you're in a room with someone.*" P19 remarked, "I pretend I'm here."

4.9.3 Other insights

Participants preferred presentation over the virtual tabletop for reasons such as a better view and it being more comfortable to grab objects, to reach to the objects and to work on the given task in comparison to the Fishtank condition. For example, p37 explained *"I actually feel like the 3D on the table was the best for me. It is how I felt like being able to like to pick something up. And move it around."* P29 said: *"It was definitely easiest even though [Hover condition]. I was trying to move it. It was really working out well." P48 mentioned: "You could just bring it up to your eyes and see what's underneath the object."*. Twenty-eight percent of participants preferred the Box condition for working on the given task. P43 explained: "*I preferred the time it was deeper in [box] I think because I'm not very tall. And so having things are deeper. It felt like I could reach deeper than go further out.*" P26: *"I personally prefer the last one [box] because I think I was comfortable with what was happening. I had a good understanding of everybody in the room. Who was talking who was louder. And from a personal comfort perspective I think."*

Overall, the result provides substantial evidence that using an IMRCE increases group awareness and decreases the presence disparity in comparison to manipulating information on a physical tabletop. However, we did not find enough evidence that projecting 3D models over the virtual tabletop increases group awareness and decreases the presence disparity in comparison to projecting 3D models within the virtual tabletop.

CHAPTER 5 IMRCE TOOLKIT

Mixed reality can be used for mixed presence collaboration by connecting physical and virtual worlds to create an integrated space. Collocated collaborators work in a physical space, and remote collaborators connect through a linked virtual space, facilitating a sense of co-presence that can benefit collaboration. We introduce IMRCE, a contemporary toolkit for such immersive mixed reality collaborative environments (IMRCE). The motivation behind IMRCE is to support designers in exploring and implementing different approaches for managing awareness and presence in MR-MP environments. IMRCE helps collaborators to update their spatial mental map of the collaborative environment by providing visual cues such as position indicators and virtual hands. IMRCE provides three key features impacting awareness and presence: positions of collaborators during collaboration are indicated, hand gestures of collaborators are shared, and physical and virtual environments are connected through virtually-physically mapped displays. The main contribution of the toolkit is its encapsulation of these three features, allowing rapid development of MR-MP systems.

In this chapter, we first explain HCI toolkit research and options for evaluating a toolkit based on previous research. We detail the architecture of IMRCE and present three examples that illustrate the flexibility and capabilities of our toolkit. Then we explain our
5.1 study design, and finally, we present the results.

5.1.1 HCI Toolkit Research

Rationale for Development of a Toolkit

Greenberg [165] defines a toolkit as a "generative platform designed to create new interactive artifacts, provide easy access to complex algorithms, enable fast prototyping of software and hardware interfaces, and/or enable creative exploration of design spaces." Ledo et al. [166] expands this definition, distinguishing toolkits from systems in the sense that systems are designed to perform limited tasks while toolkits offer generative, open-ended solutions by providing building blocks that users can be recombined and adapted. Ledo et al. [166] believe that the generative nature of toolkits gives rise to more possible designs that can readily be evaluated. The IMRCE toolkit also serves the same purpose by collapsing complicated design steps into simple steps and providing the opportunity for designers to focus on using the features IMRCE provides instead of designing them.

Ledo et al. [166] synthesized conclusions from Myers et al. [167], Olsen [168] and Greenberg [165], to arrive at five primary goals for HCI toolkits:

- Toolkits save time and reduce the complexity of designing an interactive application by condensing concepts to make things more manageable [168][165].
- Toolkits provide a new pathway for creating solutions. Specifically, they provide direction, which can help users to save time and resources [167].
- By collapsing complicated processes into simple steps, toolkits allow for a broader range of users with varying development knowledge/experience to design interactive application and solutions.
- Toolkits can be integrated within existing infrastructures and standards and allow developers to benefit from the combination of toolkits and other existing infrastructure and standards [168][169].
- Toolkits facilitate creative exploration and prototyping [169].

5.1.2 Choosing the Evaluation Method

Ledo et al. [166] studied and analyzed 68 HCI toolkit papers that were published between 2000 and 2017 in important SIGCHI venues such as CHI, Ubicomp and UIST. After analyzing and categorizing these papers, they identified four evaluation strategies that researchers can use (separately or in combination) for their toolkit research studies: (1) demonstration, (2) usage, (3) technical evaluation, and (4) heuristic evaluation. Below we summarise the results of Ledo et al.'s [166] study.

Heuristics evaluation:"Heuristics are used as a discount method that does not require human participants to gather insight, while still exposing aspects of utility" [166].

Technical evaluation is used to study the performance and efficiency of a toolkit, and it can be a complimentary evaluation of demonstration and usage evaluations.

Demonstration: In the demonstration, authors use scenarios to show the capabilities of the toolkit for creating an application.

Usage: In this technique, external users will try the toolkit, to evaluate the ease of use and clarity of concepts and to validate the value of the toolkit for the users. It is very common to measure the users' opinions. A common set of metrics is "users' opinions, preferences, completion time, the number of steps (e.g. lines of code), or some mistakes" [166].

Ledo et al. [166] describe six techniques for usage evaluation: usability study, A/B comparison, walkthrough demonstrations, observation and take-home studies.

Usability Study: A usability study helps authors to employ metrics such as time, accuracy and number of lines to measure the performance of participants and use their qualitative feedback. Giving a series of programming tasks that address different aspects of the toolkit is a common method for usability studies. [170][171][172] are examples of usability studies.

A/B Comparison: In this method, the toolkit is compared to a baseline which does not include the toolkit. Maumi [94], GroupKit [173][174] [175] and [176] are some examples of A/B comparison.

Likert scale questionnaires are a common way to collect qualitative feedback from participants such as was done in these studies [175][174][177][178]. Open-Ended Interviews is the other method for collecting data. For example, [178][179][180] used this method.

Demonstration and usage evaluation are the popular evaluation methods and are often combined with each other. 66/68 of papers that were reviewed by Ledo et al. [166] used the demonstration technique, 35/68 of them used usage techniques, and 33/68 of them used both usage and demonstration techniques. We chose to use demonstration (Replica) and usage evaluation (A/B comparison). We explain the use of the toolkit in the form of designing an immersive mixed reality collaborative environment that connects a remote participant to collocated participants. We also describe our study design, evaluation and the results.

Reviewing System Architecture

The virtual environment can allow virtual collaborators to produce virtual gestures and use their virtual embodiments during collaboration. we have designed the toolkit for
5.2 collaborative work and training experiences in mixed reality installations that allow collocated and remote collaborators to work on shared 3D content in the shared workspace with supported position and hand tracking.

With hand and indoor position tracking technology, the virtual environment can provide contextual information for both remote and collocated collaborators to increase the workplace, group, contextual, and availability awareness for collaborators.

Workplace awareness is used to describe the knowledge of tasks within the collaborative environment. IMRCE allows designers to provide shared 3D content for collaborative tasks. IMRCE synchronizes all the changes in the 3D content for all clients in real time. Therefore, all collaborators will stay informed about the ongoing activities related to the shared 3D content.

IMRCE supports position tracking, hand tracking and visualization of the results of tracking for all clients to keep all collaborators updated about the position of other collaborators and their current activities and also be aware of individuals who join/leave the collaboration space.

Group awareness describes the feeling of being involved in a group and their activities and understanding the dynamics of the group. IMRCE increases group awareness by real-time synchronization between shared 3D content, position tracking and hand tracking and also by supporting an immersive VR environment that creates the feeling of co-presence for remote and collocated collaborators.

IMRCE is a Unity-based toolkit for rapidly prototyping mixed presence collaborative environments, including but not limited to mixed reality configurations. IMRCE provides integrated support for:

- Client/server applications that facilitate remote collaboration over shared content, including 3D models.
- Six degree of freedom (DOF) interaction with objects on touch displays, including standard rotation, translation, and scaling operations (RTS).
- Six DOF interaction with objects in immersive environments using pseudo direct manipulation via in-air gesture
- Sharing of body position, orientation and hand tracking data across clients

IMRCE also provides flexibility in how data is manifested, including:

- The position of collaborators (for example, as an aura or a 3D avatar).
- Hand positions and interactions (for example, as articulated virtual hands or highlighted touch points).
- 2D interactive surfaces (e.g., tabletop or wall displays, tablets), including their relative size and location.

IMRCE installations use widely available consumer hardware, and drive shared applications written using the Unity platform.

5.2.1 Network

We aimed to provide a toolkit that enables researchers to create MR collaborative environments with highly detailed graphics while models and documents stayed connected and synchronized for all collocated and remote collaborators. First, we considered using Open Sound Control (using UDP), but after initial experimentation, we observed minor latency in the network. We did not notice the issue when both remote and collocated were working on the touch surfaces, but when we started to use Head Mount Display (HMD) to provide an immersive environment, this small delay became noticeable, and the resulted jitter increased the chance of getting motion sickness. Palmisano et al.'s [181] study showed that jittering self-motion displays induce vection to comparable non-jittering displays. We shifted to the Unity network protocol (Unet), which also uses UDP. Since Unet is integrated with the Unity architecture, it provides efficient communication with Unity clients and did not introduce latency in testing.

IMRCE lets collaborators choose to have a separate dedicated server or allows one of the clients also to play the role of the server. Using IMRCE, researchers can design a system to connect collaborators from multiple locations. We have tested our application on different networks without any network issues. For the study, participants used a local network. IMRCE helps researchers to design a system that allows collaborators to perform 3D interactions such as rotating and translating shared objects that are synchronized smoothly and without noticeable delay. The IMRCE network component does not allow two different collaborators to manipulate an object at the same time. Our algorithm manages the authority transition between the collaborators automatically and seamlessly based on the first touch (on the touch screen or inside the VE) an object receives. We wanted to support real-time synchronization of the shared content and allow collaborators to contribute to the activities without having concerns about the conflation between the changes they are making with changes that other collaborators make on the same content. This can become a more significant issue when the number of collaborators is greater. Therefore, we decided to choose IMRCE for handling the authority of content manipulation. In this way, collaborators can be sure that the changes they make to content will not be overridden by other collaborators' actions.

5.2.3 Hand Tracking Over the network

IMRCE provides support for hand tracking, to map positions, gestures, natural movements and interaction of hands to their virtual articulated hands inside the virtual environment and on the touch displays. IMRCE gives the option to designers to render virtual hands at both collocated and remote locations, on the touch displays and inside the immersive virtual environment. Visualizing collaborators' hands and their natural gestures and position support the ideas of intentional communication and contextual awareness.

Using hand tracking algorithms and visualizing them have been developed and studied before. VideoArms [81],VideoDraw [98], VideoWhiteboard [99], TeamWorkstation [100] and ClearBoard [102] are some examples of using hand tracking technology. Current methods and algorithm supports local hand tracking and visualizing them as 2D or 3D models. Some of these works allow visualizing a 2D model of hands at the remote location. However, this operates through using video capture, and it is akin to video display sharing.

IMRCE integrates Leap Motion sensors as the primary method (ready out of the box) for tracking natural hand movements and gestures of collaborators locally. The hand components of IMRCE can work with other hand tracking hardware. However, developers need to replace the Leap hands data package with the data package that comes with the alternative hand tracking device.

We developed a method, described below, to transfer hand gestures and movements over the network and have real-time synchronized articulated 3D hands on touch displays and inside virtual environments. Leap motion's virtual hands cannot turn to network objects since their algorithms are written for local users. To establish the virtual hands as a network object (network objects can be shared on the network), we duplicated the virtual hands and then removed all the original scripts and shaders from them. We named these copied hands "shadow hands." We established the shadow hands as network objects. We added a new script (called LeapSimulator) to the original hands. This script tracks all the movement of the original virtual hands and applies them to the shadow hands. IMRCE uses shadow hands to synchronize virtual hands on all the clients' applications in real time. By using our toolkit, developers/researchers can track and visualize collaborators' hands on both collocated and remote stations without the need for specialized programming.

Touch display collaborators have the option to choose if they want to see their virtual hands during collaboration or not. Also, Schwind et al. [182] in their recent study showed that "women perceive lower levels of presence while using male avatar hands and male perceive lower levels of presence using non-human avatar hands." To address this problem, IMRCE provides a user interface that allows collaborators to change the articulated hand features of gender, size, and colour. Figure 20 shows an example of hands and the representation of them in a virtual environment and on the tabletop.

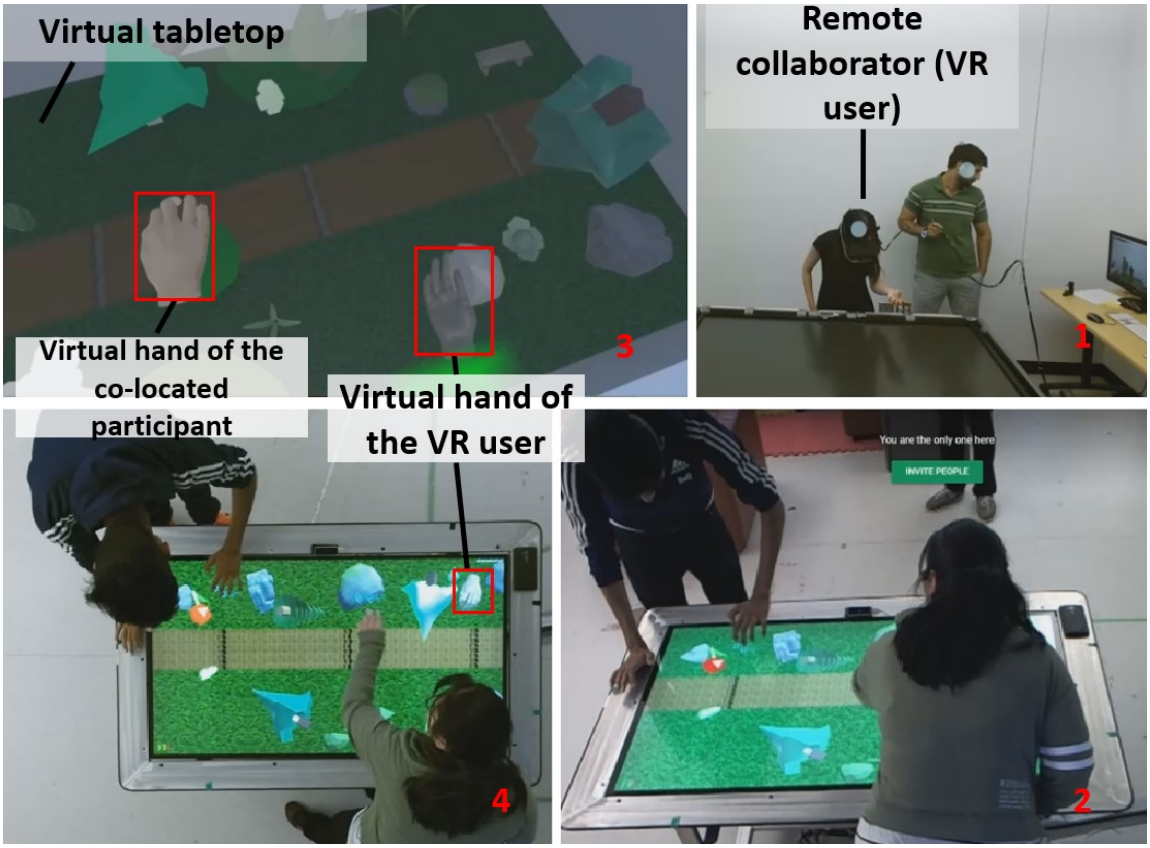

Figure 20: (1) The VR user using her hand for interacting with 3D models. (2) Collocated collaborators working around a physical tabletop that is mapped to the virtual tabletop. (3) The view of VR user inside the immersive virtual environment, the virtual hand of VR user and the mapped virtual hand of the collocated collaborator is marked. (4) top view of physical tabletop, the marked virtual hand is mapped with the hand of a remote person.

5.2.3 Position Tracking/Mapping

IMRCE was developed to be able to work with different position tracking systems. IMRCE supports the OSC protocol for communicating with position tracking systems such as the Top-Down Tracking (DT-DT) system [163] and the Kinect tracking system. IMRCE is flexible regarding the use of all or just part of these data. Tracking the location of collaborators aims to provide more context for collaborators to increase their awareness of actions that are coupled with the workspace.

Tracking the position of HMD users lets IMRCE map the movement of the HMD users in the immersive virtual environment. This feature allows collaborators to have more realistic and natural collaboration. For example, collaborators with an HMD can move in the physical environment and have that action reflected in the virtual environment.

5.2.4 Interaction with 3D Objects on the Touch Displays

IMRCE provides six degrees of freedom (DOF) for interacting with 3D objects on a touch display, like most touch-enabled 3D modelling and viewer software. IMRCE provides a multi-user interface: collaborators can work on different objects on the touch display simultaneously, and their touches do not interfere with other collaborators touch actions who are working on the same touch display with different objects. Similar to other toolkits for touch interaction such as Sticky tools [78] screen-space [79], and Depth-Separated Screen-Space [80], IMRCE provides support for Rotation-Scale-Translation (RST) gestures: one finger for transformations, two fingers for rotations, and three finger pinching in to lift an object as well as pinching out for scaling. It is essential that a collaborator's touch initialize on the object, but it is not necessary for the contact points to remain on the object. For example, a collaborator can touch a 3D cube with two fingers as long as those two fingers stay in contact with the touch display, the collaborator can move their fingers around to rotate the object in the desired directions. We used the TouchScript[1] API to identify touch points on the touchscreen.

5.2.5 Interaction with 3D Objects Inside an Immersive Virtual Environment

Using Leap motion sensors, HMD users always see their mapped virtual hands inside the immersive virtual environment unless developers disable this feature. The virtual hands are realistic and sufficiently detailed to provide a sense of natural hand interaction while working with 3D models. Collaborators inside the immersive virtual environment can grab 3D objects and move or rotate them. IMRCE presents HMD users' hands across the

[1] touchscript.github.io

network on touch displays and inside immersive virtual environment(s). HMD users can grab the objects, point to them, and use their hands to express and illustrate their verbal communications.

Functionality Overview

Figure 21 shows a sequence diagram view of IMRCE network communication for a mixed reality scenario that connects collocated collaborators around a touch-enabled tabletop
5.3 display, to a remote collaborator who wears an HMD to connect to the shared collaborative space. The remote collaborator sees a virtual representation of the collocated collaborators' location, including a virtual model of the tabletop display.

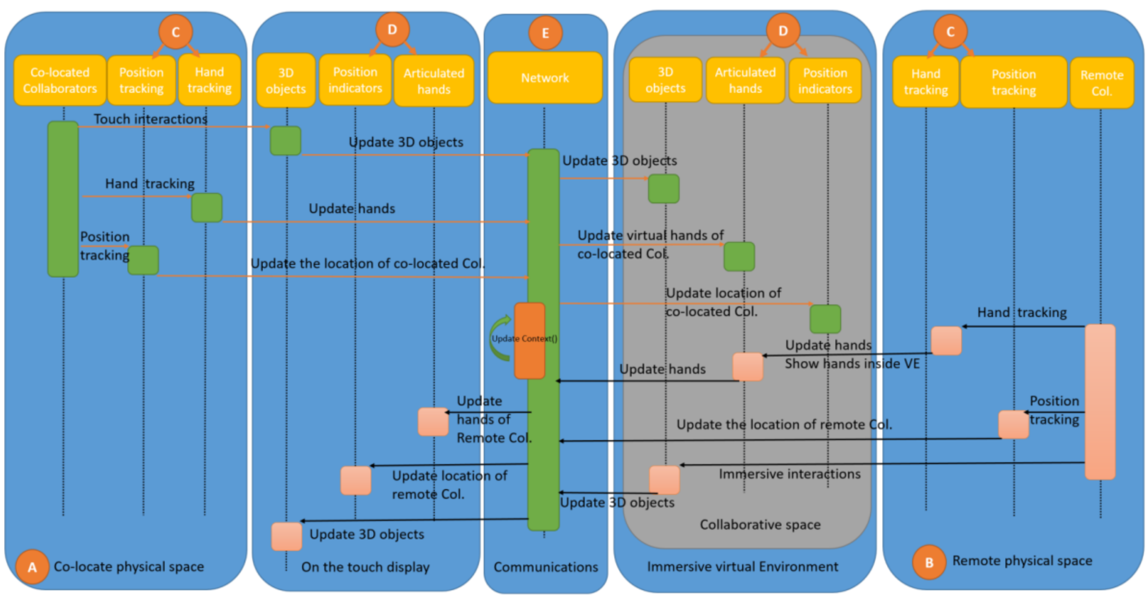

Figure 21: Sequence diagram for IMRCE. (A) Collocated collaborators using touch displays to interact with 3D content. (B) Remote collaborators use their hand to interact with 3D content inside an immersive environment. (E) The server receives the changes in 3D content. The server synchronizes 3D objects in a shared workspace. Therefore, all collaborators can see the results in real time. (C, D) Hand tracking sensors and position tracking sensors continuously keep track of collaborators hands (positions and gestures) and collaborators hands positions relative to the shared workspace. (E) The server uses data provided by tracking sensors to update articulated hands and position indicators for all clients.

A. Collocated collaborators stand around physical touch tabletop; the tabletop shows the application that was developed with the IMRCE toolkit.

B. Remote collaborator wears an HMD, and they are immersed in a virtual environment. They stand around a virtual tabletop that is mapped to the physical tabletop using the IMRCE toolkit.
C. There are hand tracking sensors and position tracking sensors at both the remote and collocated locations.
D. The position of collaborators around the physical/virtual tabletop is tracked and visualized at all locations in real time (inside the virtual environment and on the touch displays). Collaborators hand gestures and positions are also tracked and visualized at all locations in real time. Researchers/developers can choose either to show or not to show the virtual hands of collocated participants to themselves. For example, if participant A stands around a physical tabletop, her hands would be tracked and shown at other locations, but it will not be shown to her by default.
E. IMRCE allows researchers to have a dedicated server or let one of the clients act as a server. In either case, the packages will be sent to the server, and the server will update all other clients. The server controls the authority of users working with shared items. For example, if user A grabs a shared 3D model with her virtual hand, the server will give the ownership of that item to that client and will not accept updates from other clients. IMRCE changes the brightness of selected items by default as an indication that the object is in use. However, the researcher can disable this feature.

5.4 Working with IMRCE

The IMRCE toolkit was designed for the Unity game engine. Unity supports cross-platform applications which can be compiled and used on devices with different operating systems. Unity also provides a programming GUI supporting component drag&drop, property modification, and custom extensions, which reduces the amount of coding developers need to do to use the toolkit.

An IMRCE system should have a server, and at least two clients (VR, touch or both). To serve as a demonstration of the process of using IMRCE, we describe a simple application we created consisting of a touch application for a physical touch tabletop, a server application and a VR application and with position tracking and hand tracking for both VR and touch display. A cube and a sphere are the shared objects. After importing the IMRCE unity package to the project, the steps below can be taken to use the toolkit.

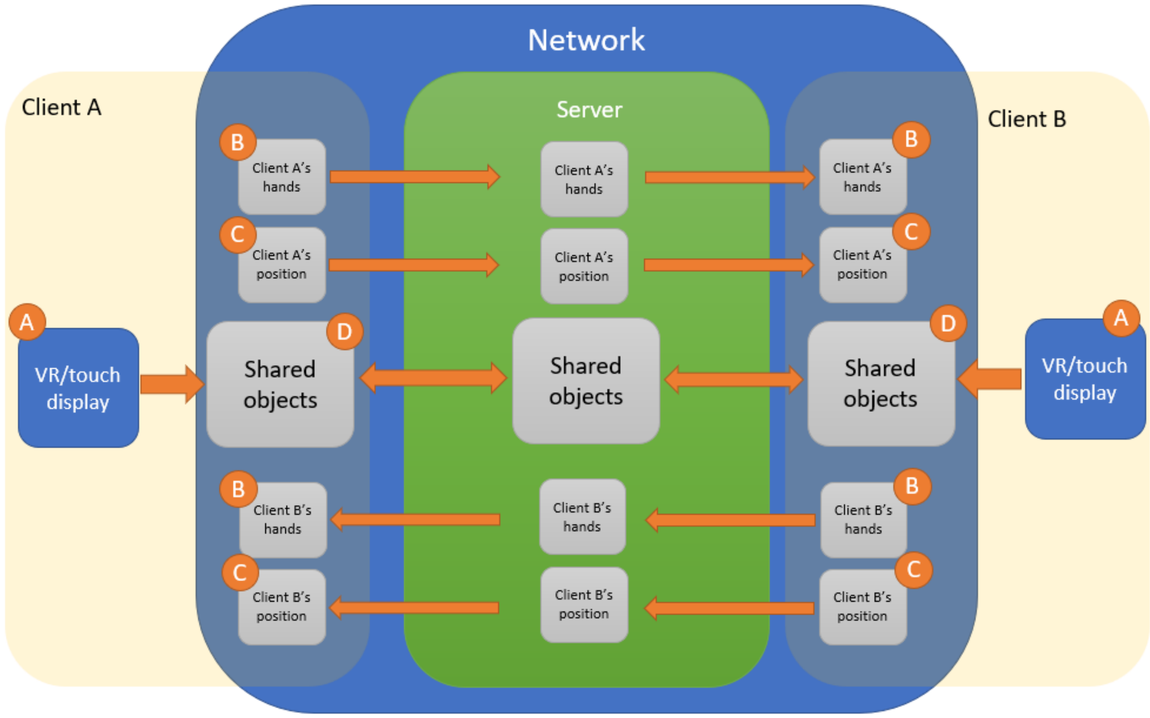

Figure 22: The touch display and the VR environment are local components. The server spawns the shared objects including virtual hands and position indicators. IMRCE transfers the temporary ownership of an object between clients based on touching or grabbing shared objects on the touch screen and inside the VR environment, respectively. Only a client that has ownership can manipulate the object. IMRCE also synchronizes objects between all clients. The server also spans virtual hands and position indicators and gives the permanent ownership of them to the related client. For example, only client A can use Client A's virtual hands. Another client can see her gestures, but they cannot use Client A's virtual hands.

5.4.1 Network Initialization (both clients and server)

To set up the network, the 'NetworkEssentialServer' and the 'NetworkEssentialClient' prefabs'[2] should be added to the server and client scenes, respectively. These prefabs have

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[2] "Prefab is a type of asset that allows you to store a 'GameObject' object complete with components and properties. The prefab acts as a template from which you can create new object instances in the scene" [199].

three main components: ‘ModelSpawner,’ ‘NetworkManager,’ ‘network discovery’ and ‘Fake.’ The Fake prefab should be registered as the ‘PlayerPrefab’ under ‘NetworkManager.’ Figure 23 shows NetworkEssentialServer’ and its components and how to add network prefabs to the scene.

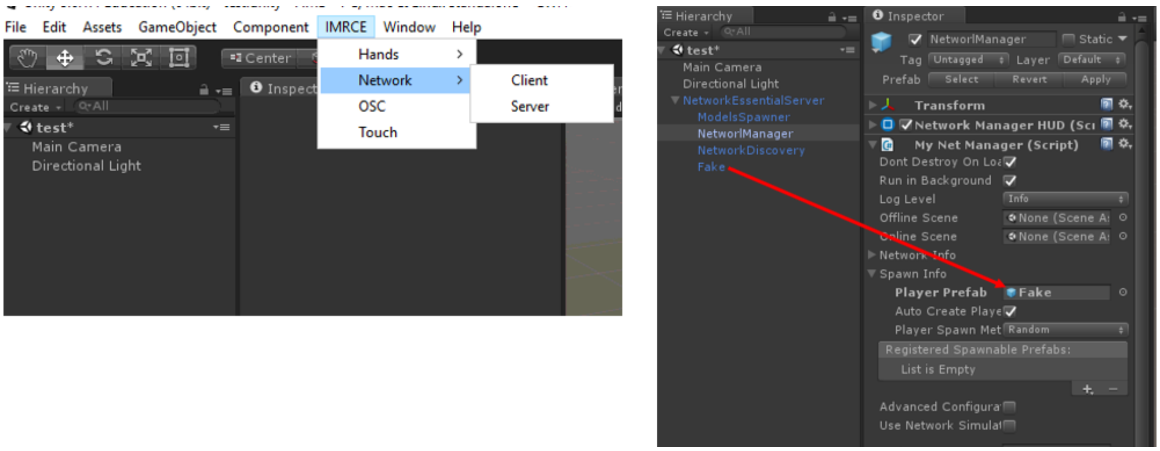

Figure 23: Right: adding the Network client/server to the scene from the IMRCE menu. Left: ‘NetworkEssentialServer’ and its components. ‘NetworkEssentialClien’ has the same components.

5.4.1.1 Setting up Object Synchronization (both clients and server)

On both the server and client applications, shared objects should be established as network objects. To do this, after choosing the 3D object (cube and sphere in our example), the initialize option should be selected from ‘component/IRMCE’ menu. Figure 25 shows how to add network components to the sphere.

After adding network components, shared objects should be registered under ‘network manager’ to be recognized as network objects. This can be done by dragging and dropping the objects prefab under the network manager. Figure 24 shows the example of sphere and cube. Virtual hands and positions indicators are also considered as shared objects, but they have the network component by default. Therefore, the developer can skip the network initialization step for virtual hands and positions indicators. However, these components should register under ‘network manager’ at both client and server applications.

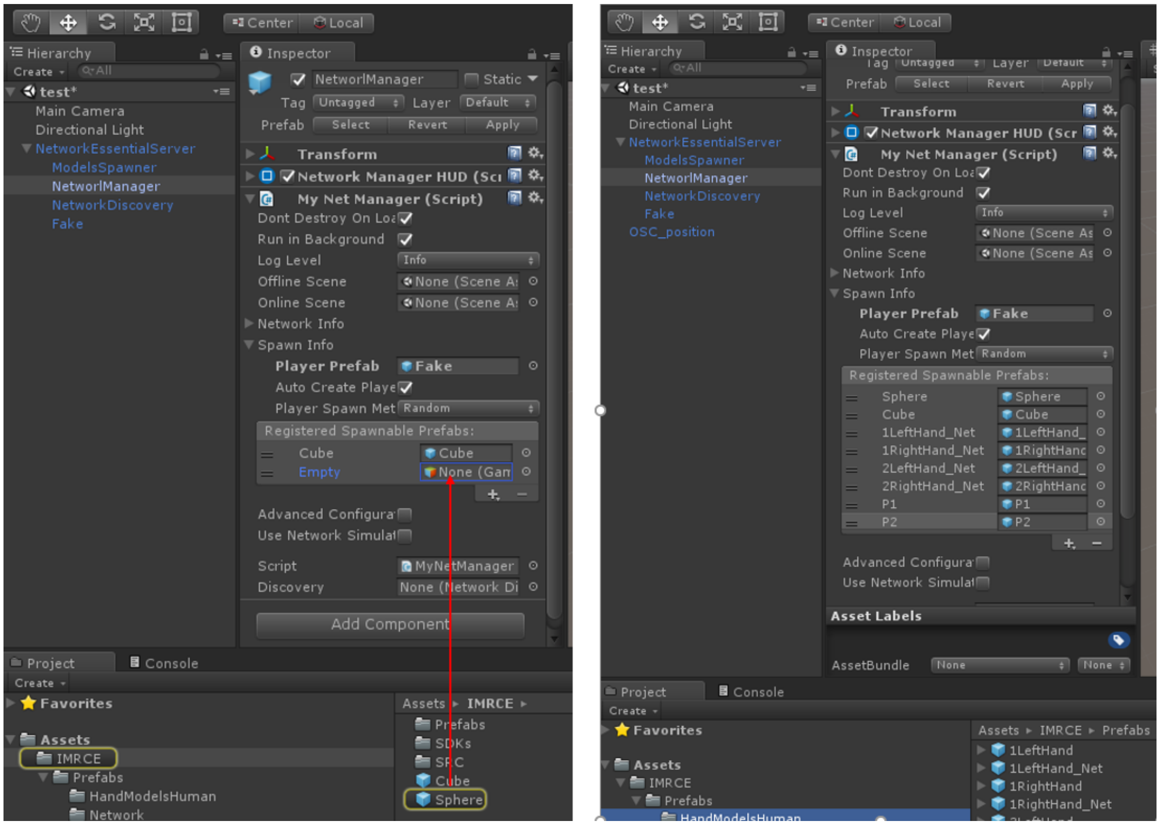

Figure 24: Left: Registering sphere under network manager for the server. Right: virtual hands and positions indicators also need to be registered under network manager at both client and server applications.

5.4.1.2 On the Server Application

The server is responsible for spawning 3D objects. When the server is spawning 3D objects, they will appear on clients' devices. To spawn shared objects on the server, including virtual hands and position indicators, they should also be registered under the 'ModelsSpawner' component. Figure 26 shows the line of codes that need to be added to the script for each model and how 'ModelsSpawner' should be added to the application scene.

5.4.2 Setting up Position Tracking on Clients

Position indicators are also considered as shared objects. The server spawns the position indicators and gives client(s) permanent ownership of them. Each client application has the ownership of the position indicator(s) of its users. The DT-DT system [163] uses a top-down Kinect camera to track users. It uses OSC protocol to broadcast the results on the network.

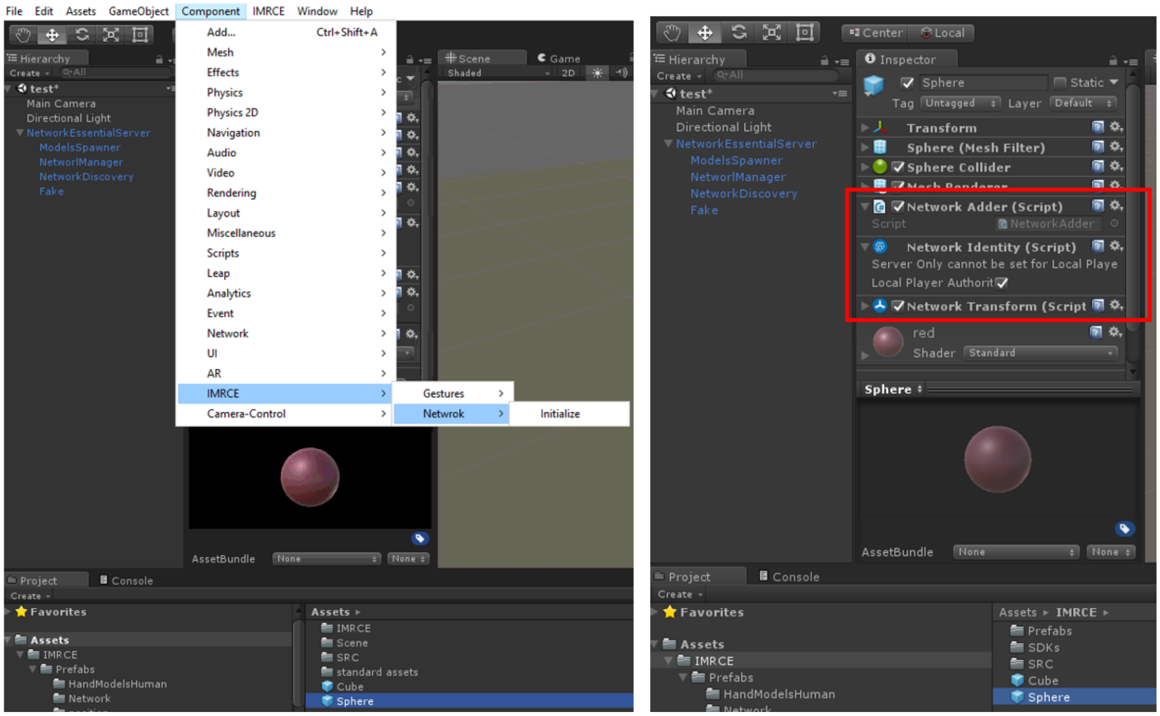

Figure 25: Left: Making the sphere a network object, right: shows sphere after adding network components.

Each OSC package must be formatted in the following order, as displayed in Table 9: Number of users that have been tracked, ID of each user, and the position of each user. Developers need to add the OSC prefab to the scenes using the IMRCE menu. Also, the 'probeOSC' script should be modified to calibrate the scaling to proper values for the scene and physical location that developers are planning to have. Position indicators should be registered under 'NetworkManager' at both the client and server applications and under 'ModelsSpawner' at the server application. Shows the 'OSC_position' prefab and its script.

Table 9: OSC data format for tracing the package

#users	ID1	X1	Y1	Z1	...	IDn	Xn	Yn	Zn

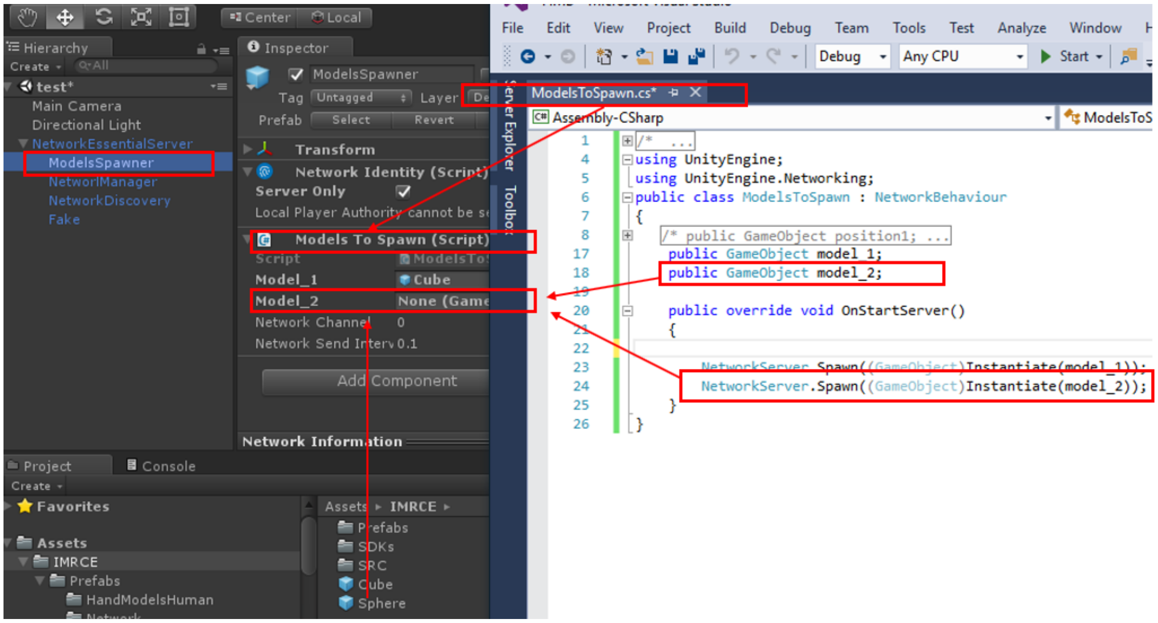

Figure 26: Right: registering Sphere object under the ModelsPawner component. Left: for each object, these two lines of code should be added to the 'ModelsToSpawn' script.

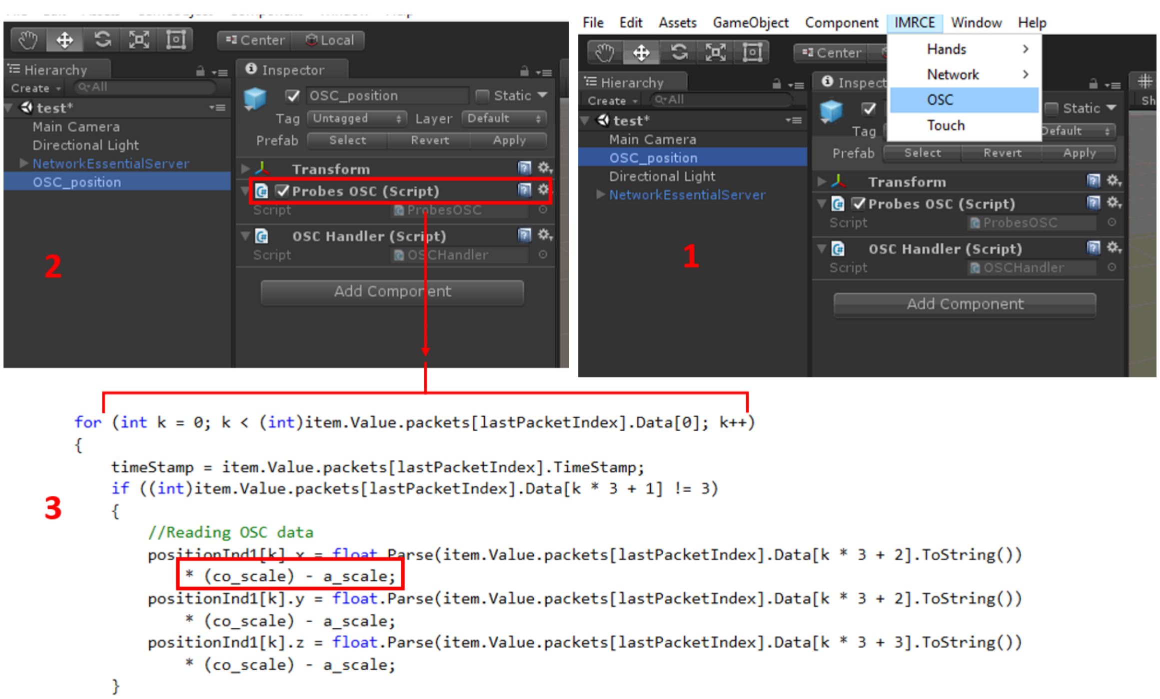

Figure 27: (1) Adding 'OSC_position' prefab to the scene from IMRCE menu. (2) 'ProbeOSC' needs to be edited. (3) Scripts need to be edited for proper scaling.

5.4.3 Adding Hand Tracking

For clients who are using a touchscreen, the developer should add the ‘LeapTouch’ prefab to the client scene. Moreover, for clients who are supposed to use an HMD, the developer should add the ‘VRHeadMount’ prefab. Figure 28 shows how to add these two prefabs to the scene from the IMRCE menu. Virtual hands should be registered under ‘NetworkManager’ at both the client and server applications and under ‘ModelsSpawner’ at the server application.

5.4.4 VR environment

We are using a custom prefab to enable HMD use in the immersive environment. This prefab, ‘VRHeadMount,’ has the necessary components for using virtual hands and synchronizes its movement and gestures for all clients. Figure 28 (left) shows how to add the prefab from the IMRCE menu.

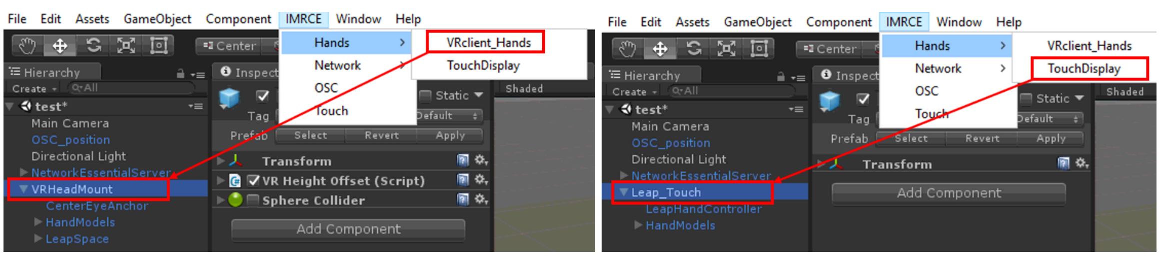

Figure 28: Left: adding ‘VRHeadMount’ prefab for enabling HMD and enabling hand tracking for the VR user. Right: Adding ‘Leap_Tocuh’ prefab for enabling hand tracking for touch display users.

5.4.5 Enabling Touch

To enable touch for a client that uses the touchscreen, the developer should add the touch prefab to the project scene from the IMRCE menu. Figure 29 (Left) shows how to add the ‘Touch’ prefab to the touch client scene.

To enable touch sense and touch gestures for each object, specific components should be added to the object from the IMRCE component menu. The first one is the ‘transform’ component which enables touch sensing for the object. After that, the developer can add desired gesture to the object through the IMRCE component menu. Figure 29 shows how to enable the touch feature and enable touch gestures for an object. Again, IMRCE is using ‘Tocuhscript’ API to identify the touch points and define gestures.

Figure 30 shows the server ready application and Figure 31 shows the client ready application for the touch display and the VR environment.

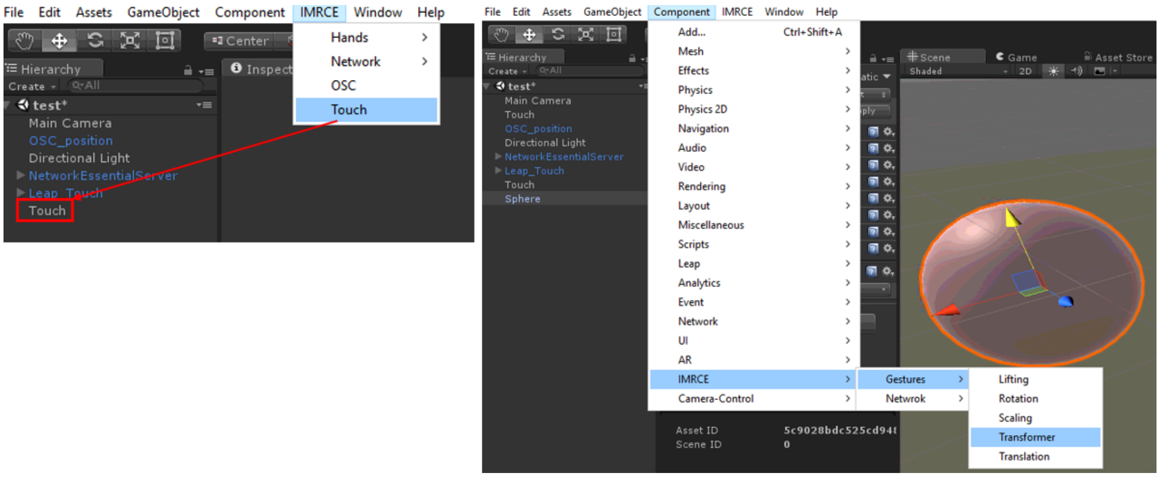

Figure 29: Left- adding the Touch prefab to the scene to activate touch layer for the application. Right: adding 'Transformer' to the game object (cube) is necessary to activate touch recognition. After that, the designer can add any of the gestures (lifting, rotating)

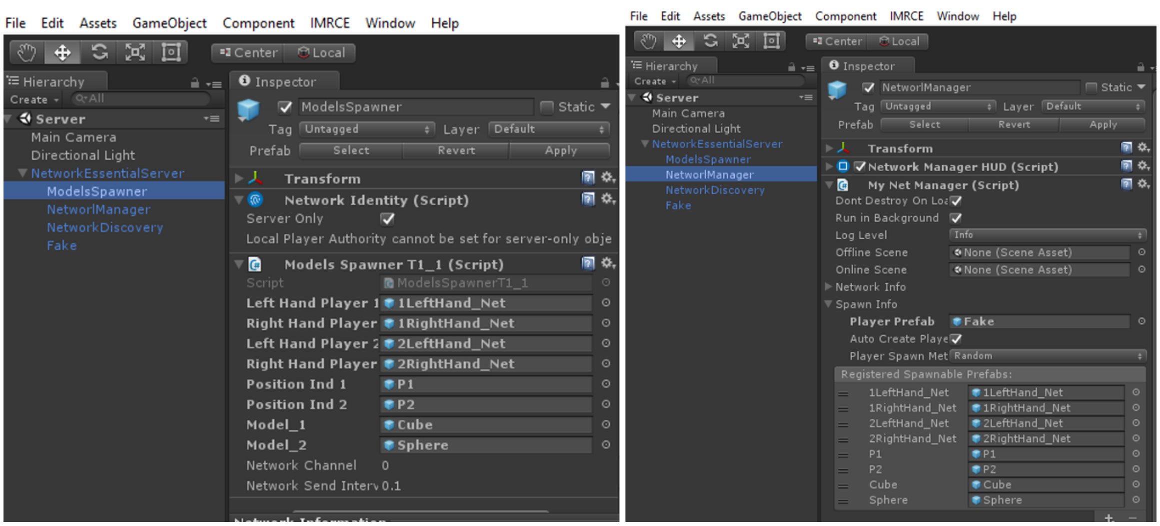

Figure 30: Ready server, Left: the registered object under 'ModelsSpawner.' Right: the registered object under 'ModelsSpawner.'

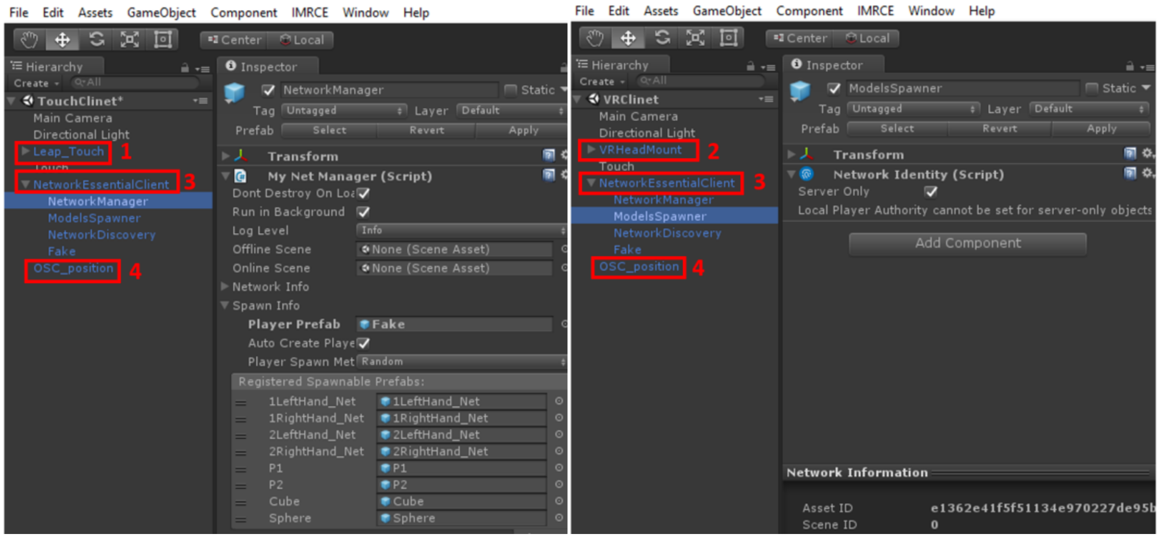

Figure 31: Client ready applications for Touch display (right) and VR environment (left). (1) Touch prefab for touch application. (2) VR_Hand prefab for VR environment. (3) Network prefab (4) OSC prefab for connecting the position tracking system.

5.5 Study Design

We used usage evaluation (A/B comparison) to explore whether the IMRCE toolkit helps developers to develop mixed reality systems in less time and with less program ambiguity in comparison to the condition in which they did not use the IMRCE toolkit. We asked our participants to perform a series of tasks using IMRCE and without using IMRCE over two days of programming.

5.5.1 General Study Design

We recruited ten university students who had experience working with Unity (two female, eight males, 21-25 years old). We divided our participants into two groups of five. Each group participated in the study for 11 hours over two consequence days (5.5 hours per day). Participants in each group worked independently on the given tasks. We made sure that each participant worked on their application separately and they did not sit or work together. The main reason to have two groups was the length of the study, and that we did not allow participants to have any type of group collaboration except in the final interview.

Five participants were in a common meeting room with access to a full HD 55” physical tabletop to test their applications. We also provided two touch windows tablets for testing touch applications. We set up the DT-DT position tracking system to track people around the physical tabletop. DT-DT was broadcasting the results in the form of OSC packages. Therefore, everybody could receive the packages on their computers. We also provided five Leap hand tracking sensors for the participants. An Oculus Rift HMD, which was running on a gaming desktop computer (Core i7, 3.4 GHz, GTX1070), was also set up in the room and participants could try their VR application on it. All our participants used their laptop for programming for the duration of the study. However, they could choose to use the computer we provided for them.

One researcher was always present during the study to answer questions regarding hardware setup and the top down tracking system. The researcher did not answer questions about working with IMRCE or other libraries. We counted the number of questions participants asked and we took note of the questions for analysis.

After each condition, participants answered a questionnaire that asked them to assess their experiences with programming the given tasks. We also interviewed participants together at the end of each condition to learn about their experiences and opinions about programming with or without the IMRCE toolkit. There were five steps to finish the given task; participants had limited time for each step. We had the completed components for each step so if a participant could not finish a step in the given timeframe then our researcher imported the component into their project so that they could continue to the next level. Participants had a 15-minute break between each step. Participants had 90 minutes for the second step and 60 minutes for each of the other steps. We timed the task separately for each participant and all participants received their 15 minutes of break. In other words, it was not necessary for participants to start and finish each step with each other.

We kept note of the time that each participant took to finish a task. We also counted the number of lines of code and number of problems while running the task. We used five scales to measure the completion of a task: five if the task was completed and could run without any problems; four if the task was completed, but there were problems and errors while running the task; three if the main parts of algorithm or components were used, but the program could not be run; two if some of the algorithm and components were present; otherwise we assigned one.

5.5.1.1 Conditions

In the IMRCE condition, participants worked on the assigned prototyping task using the IMRCE toolkit. In the NO-IMRCE condition, we provided a set of libraries that could help participants complete the same prototyping task. These were TouchScript [183], LeanTouch [184], Simple Touch Controller [185], Simple Touch Camera Script [186], Fingers Lite [187], UnityOSC [188], UNET Basic [189], Photon Unity [190], and Leap motion [186]. We asked participants if they had experience with any of the libraries/APIs. All participants had experience with the Unity network system (UNET), six of them had used Photon Unity [190], seven participants used Leap motion libraries [186], for touch UI two participants used TouchScript [183] and three of them had used LeanTouch [184]. None had used the remaining libraries before.

We asked participants if they had experience with any of the libraries/APIs. Their answers show that all the participants had experience with Unity network system (Unet), six of them had also used Photon Unity before, seven participants had used Leap motion libraries before, two participants had used the TouchScript and three of them had used LeanTouch before.

Each group had two to five and half hours to finish the tasks under each condition (over two days). To counterbalance the study, the first group worked on the tasks without using the IMRCE on the first day, and then they used IMRCE on the second day. The second group used the IMRCE on the first day, and they worked on the tasks without using the IMRCE on the second day.

We explained how to use the IMRCE toolkit for 20 minutes before the IMRCE condition. We explained different algorithms, libraries and tools that participants could use to complete the tasks without using the IMRCE toolkit for one hour before the No-IMRCE condition. We introduced Leap motion SDK and how to use it for hand tracking. We explained the mechanism of identifying touch points on a touch screen and how to use them to create gestures. We showed an example of creating a hand gesture using the Unity library (using five fingers to scale a cube). We showed how to create an OSC client with Unity and receive packages using UnityOSC. Again, we did not recommend using any specific library or toolkit for the No-IMRCE condition.

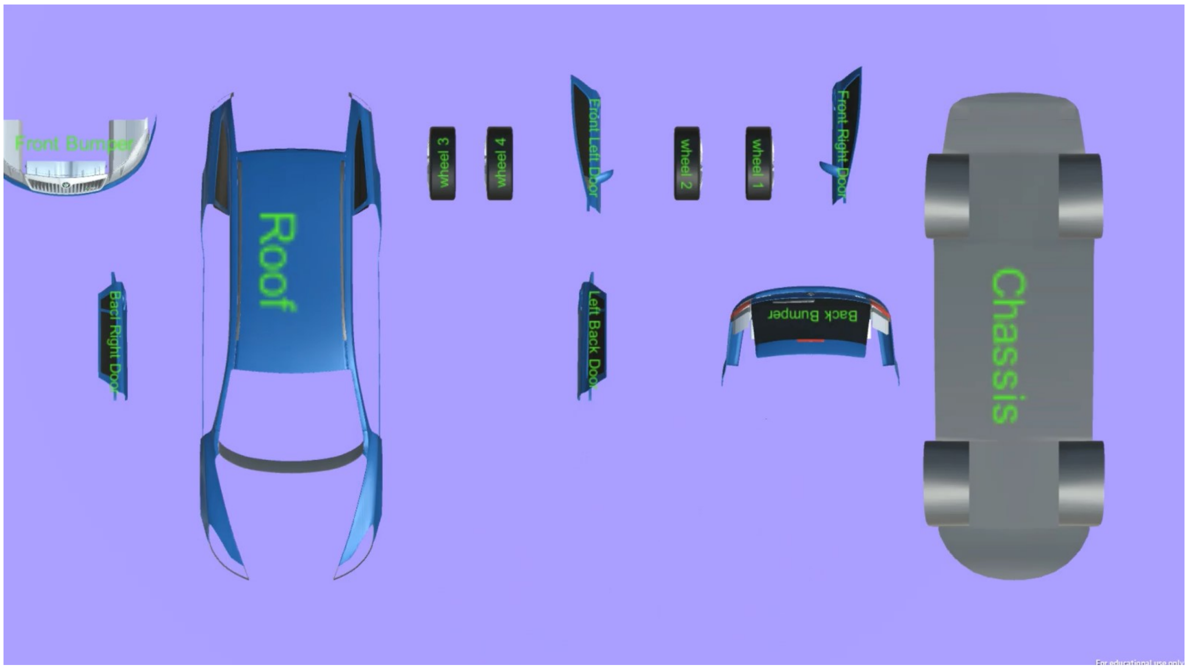

Figure 32: Replica of the car

5.5.1.2 Activities

We defined a collaborative system for participants to design. This system is supposed to connect three collaborators with each other to work on a replica of a car that is shared between them. One of these collaborators uses a touch tabletop, one of them uses a touch windows tablet and the other collaborator uses an HMD. Collaborators were supposed to see each other's positions and virtual hands while working on the replica.

We broke down the activity into five steps:

1. Setting up the server and client applications.
2. Adding touch components that allow a collaborator to work on the shared objects on the physical tabletop and the windows tablet (No VR, hand tracking or position tracking).
3. Adding position tracking to the previous application.

4. Adding (network) hand tracking to the previous application.
5. Creating a VR application with hand and position tracking that can connect to the previous application.

If a participant did not finish a step in the allotted time frame, we completed for them so that they could move to the next step. Figure 32: shows the result of the task.

5.6 Data Collection

We used four methods to collect data from our participants: demographic and postcondition questionnaires, postcondition interview (group), observation notes such as questions that were asked by participants and time to finish each task, and reviewing their programs for usability analysis. Our researchers wrote down the participants' answers during the postcondition interviews for analysis.

We selected five parameters as outlined by Ledo et al. [166] for evaluating the usability of IMRCE: time to finish the study, level of completion, number of lines of code, number of questions and number of problems. We measured the time each participates worked on each step.

5.7 Results

5.7.1 Working with external libraries (No-IMRCE)

We did not find a toolkit that provides all the functionality that IMRCE provides in one package; therefore, we provided a list of libraries and APIs that could help participants in their programming. This list just was a suggestion and participants did not need to choose any of the libraries or APIs, and they could use any other method that they preferred.

First step (setting client/server): Four participants used the Photon library and six participants used Unity Unet (Unity library). All participants completed the task. The average time to complete this step with Photon, Untiy Unet and IMRCE was 79.5, 48.6 and 29.8 minutes, respectively.

Second step (Setting the touch application): Two participants used Unity API and they did not complete the step, five participants used the TouchScript library and two of them did not complete the step, and finally, three participants used the LeanTouch library and one of them did not complete the task. The average time participants worked with Unity API, TouchScript, LeanTouch and IMRCE were 87.5, 78.2, 73.3 and 40.7 minutes, respectively.

Step 3 (Setting position tracking): All participants used UnityOSC and only one of them did not finish the task. The average time participants worked with UnityOSC and IMRCE were 41.5, and 31.5 minutes, respectively.

Step 4 (Setting Virtual Hands): All participants used Leap SDK and they were successful to set up the hands locally, but none of the participants could turn the virtual hands into network hands. Participants did not find any libraries that could help them with this step nor did we identify suitable libraries in advance of the study. The average time participants worked on this step was 60 minutes (maximum time) and with IMRCE the average time was 32.1 minutes.

Step 5 (VR User): All participants used the built-in support of Unity software for adding a VR user. And all of them were successful in completing the task. The average time that participants worked with Unity API and IMRCE was 43.8, and 40.2 minutes, respectively.

Overall for the No-IMRCE condition, we did not find any relation between the libraries and the time that the participants spent on each step.

5.7.2 Usability Analysis of Programming Tasks

We used paired sample T-tests on the results for each step and for the completed study. There are significant differences between developing a collaborative environment with and without the IMRCE toolkit for all six parameters, in favour of IMRCE. Table 10 shows the results of the paired samples T-tests.

Table 10: Results of paired samples T-tests on the data of the completed study.

	P_{value}	95% Confidence Interval of the Difference		Mean I = IMRCE NI = No-IMRCE	
		Lower	Upper		
Time to complete the task	$<10^{-7}$	80.16	I	I	174.3
			NI	NI	268
Level of completion	$<10^{-7}$	-28.28	I	I	89.5%
			NI	NI	66%
Number of lines of code	$<10^{-7}$	164.6	I	I	83.1
			NI	NI	259.6
Number of questions	0.025	-8.676	I	I	6.3
			NI	NI	11
Number of problems	0.033	-4.743	I	I	3.8
			NI	NI	6.3
Problems/ (LOC) *	0.059	-0.006	I	I	0.303
				NI	0.179

5.7.2.1 Time to Complete

There was a significant effect of condition on 'time to complete', $T(9) = 15.655$, $p = 10^{-7}$. Participants spent less time overall when using IMRCE (M = 174.3) than without (M = 268), although the difference in each step varied outlined below. P6 said: *"It is definitely faster and easier to use the toolkit."* P8: *"Everything was in the package, I didn't spend time on finding right libraries and algorithms*."

The difference in time to complete each step varied between conditions, as follows:

Step 1 (setting up client/server): in the No-IMRCE condition, four participants used the Photon library and six participants used Unity UNET. All participants completed the task. The average time to complete this step with Photon, Untiy UNET and IMRCE was 79.5, 48.6 and 29.8 minutes, respectively.

Step 2 (touch clients): in the No-IMRCE condition, two participants used the Unity API and did not complete the step, five participants used the TouchScript library and two of them did not complete the step, and finally, three participants used the LeanTouch library and one of them did not complete the step. The average time participants worked with

Unity API, TouchScript, LeanTouch and IMRCE were 87.5, 78.2, 73.3 and 40.7 minutes, respectively.

Step 3 (position tracking): participants used UnityOSC in the No-IMRCE condition and only one of them did not finish the step. The average time participants worked with UnityOSC and IMRCE were 41.5, and 31.5 minutes, respectively.

Step 4 (hand tracking): All participants used the Leap SDK in No-IMRCE and were successful to set up the hands locally, but none of the participants could turn the virtual hands into network hands. Participants did not find any libraries that could help them with this step nor did we identify suitable libraries in advance of the study. The average time participants worked on this step was 60 minutes (maximum time) and with IMRCE the average time was 32.1 minutes.

Step 5 (immersive client): in No-IMRCE, all participants used the built-in support in Unity for immersive displays, and all were successful in completing the step. The average time that participants worked with on this step with the Unity API and IMRCE was 43.8, and 40.2 minutes, respectively.

5.7.2.2 Level of Completion

There was a significant effect of the condition on the level of completion of the application, $T(9) = -11.112$, $p = 10^{-7}$. Participants were more successful in completing the application with IMRCE ($M = 89.5$) compared to completing the task without the toolkit ($M = 66$).

While working with the IMRCE toolkit, all participants finished all the steps without any significant help from our researcher, except one case when the developer could not add virtual hands to his application. However, none of our participants could finish all the steps in the No-IMRCE condition. Five participants could not finish setting up client/server. The Unity network is designed for multiplayer games. A game usually has a main player and series of non-player characters (NPC). The server always controls the NPCs (holds ownership) and clients only control the local player. For a collaborative application, it is necessary that clients also control the NPC objects (for example to rotate an object).

Transferring the ownership from the server to a client and returning it to the server again is not supported by Unity's default networking prefabs. Therefore, participants had to write the necessary scripts to handle this process while they were not using the IMRCE toolkit. P9 mentioned: *"I couldn't figure it out… it was a straightforward problem, but I didn't solve it."* P5 said: *"I prefer those default network prefabs [Unity network prefabs], but I think for a game like the one we were working on, I will prefer to use the toolkit [IMRCE]."*

Adding the virtual hands to the system required two main steps. The first part was adding the virtual hand to a local application. Adding a local virtual hand is simple since the Leap motion sensor SDK provides the necessary prefabs to add the virtual hands to a local application. For the second part, participants were required to add virtual hands to the network and ensure that they are synchronized and visualized on the clients. There is no support from the Leap SDK for networking virtual hands. To the best of our knowledge, there are no libraries or tools for this purpose beyond IMRCE. All participants were successful in adding local virtual hand for both conditions, but none of them could add networking to the virtual hands without the IMRCE toolkit.

5.7.2.3 Lines of Code

There was a significant effect of the condition used on the number of lines that participants coded while developing the application, $T(9) = 33.552$, $p = 10^{-7}$. Participants had fewer lines of code when using IMRCE ($M = 83.1$) compared to completing the task without the toolkit ($M = 259.6$).

Using IMRCE helped developers to significantly reduce the number of lines they coded by factor of three. P2 mentioned, *"I didn't need to program everything."* P5 explained that: *"I liked that the prefabs were there. I didn't need to think about creating them or writing scripts."* P7 said: *"I think those prefabs helped because you think about other parts of the application."*

5.7.2.4 Number of Questions

There was a significant effect of the condition used on the number of questions that were asked by participants while developing the application, $T(9) = -2.674$, $p = 0.025$.

Participants asked fewer questions when developing a program with the IMRCE toolkit (M = 6.3) compared to completing the task without the toolkit (M = 11).

We compiled the questions that participants asked us. In total, the number of questions were asked during the IMRCE and No-IMRCE condition were 63 and 118 questions, respectively. Respectively for IMRCE and No-IMRCE conditions, participants asked questions about setting up the network for client/server applications (7, 17), developing touch application (16, 29), how to work with the OSC package and how to map the results of position tracking using position indicators (12, 20), setting virtual hands (17, 32), and developing the VR application (11, 20).

5.7.2.5 Number of Problems.

Problems refer to problems with 3D object interaction on touch displays (rotation, scaling, translation), 3D object interaction in VR (grabbing, rotating, moving), position and hand tracking and synchronization of these on other clients' devices, problems with the client/server configuration, and finally problems with synchronization of shared data and objects.

Users should be able to perform RTS interaction on 3D parts of the car on both Touch tabletop and Touch tablet. The VR user should be able to grab and perform RTS using HMD. All the interactions should be synchronized for all clients. Also, each client should see the virtual hands and position of other clients. After the study finished, we ran the server and client applications, and tried to perform RTS operations on all 3D model elements using each client/device. We used the same testing procedure for all applications.

There was a significant effect of the condition used on the number of problems in the applications that participants developed, $T(9) = -2.521$, $p = 0.033$. We found fewer problems in the applications developed with IMRCE (M = 3.8) in comparison to the No-IMRCE condition (M = 6.3). Applications developed without IMRCE had more problems, especially problems related to networking and position tracking.

We thought that the number of problems might correlate with the number of lines coded by each participant (LOC). Therefore, we also considered a scale of the number of problems divided by LOC. Doing this indicated that there were no differences between IMRCE and non-IMRCE conditions for number of problems generated.

5.7.3 Questionnaires Results

Participants filled in a background questionnaire about their prior experience working with Unity 3D and C# language (main language to work with Unity 3D). Participants also filled in questionnaires after each of the five design stages that asked them about their experience working on the given task. Post-task questionnaires provided data about preferences for working with or without IMRCE and data on the usability of using IMRCE in comparison to not use the toolkit.

5.7.3.1 Background Questionnaire

The background questionnaire showed that all our participants had used Unity 3D software before and had experienced with 3D modelling software. 9/10 participants had experience developing VR application (s) for HMDs. All our participants were familiar with C# programming.

5.7.3.2 Post Condition Questionnaire

Post condition questionnaires asked for agreement on two basic statements: *satisfaction with the results* for each step, and *satisfaction with the toolkit* used for each step. Figure 33 shows the results of participants' satisfaction with the results for IMRCE (I) and no-IMRCE (NI) conditions, and Figure 34 shows the results for satisfaction with the toolkit and approach taken.

We ran paired sample T-tests on the results of the questionnaire for each step to test both usabilities of using IMRCE in developing a collaborative environment without IMRCE, and the developers' preference between the two conditions.

For satisfaction with result, there was a significant effect of condition for step 1 (setting up client/server), $Z = -2.598$, $p = 0.009$. Participants were more satisfied with their results for

IMRCE (M = 3.3, SD = 0.675) than No-IMRCE (M = 2.296, SD = 0.632). We did not find a significant difference in satisfaction with toolkit used for the same step, however.

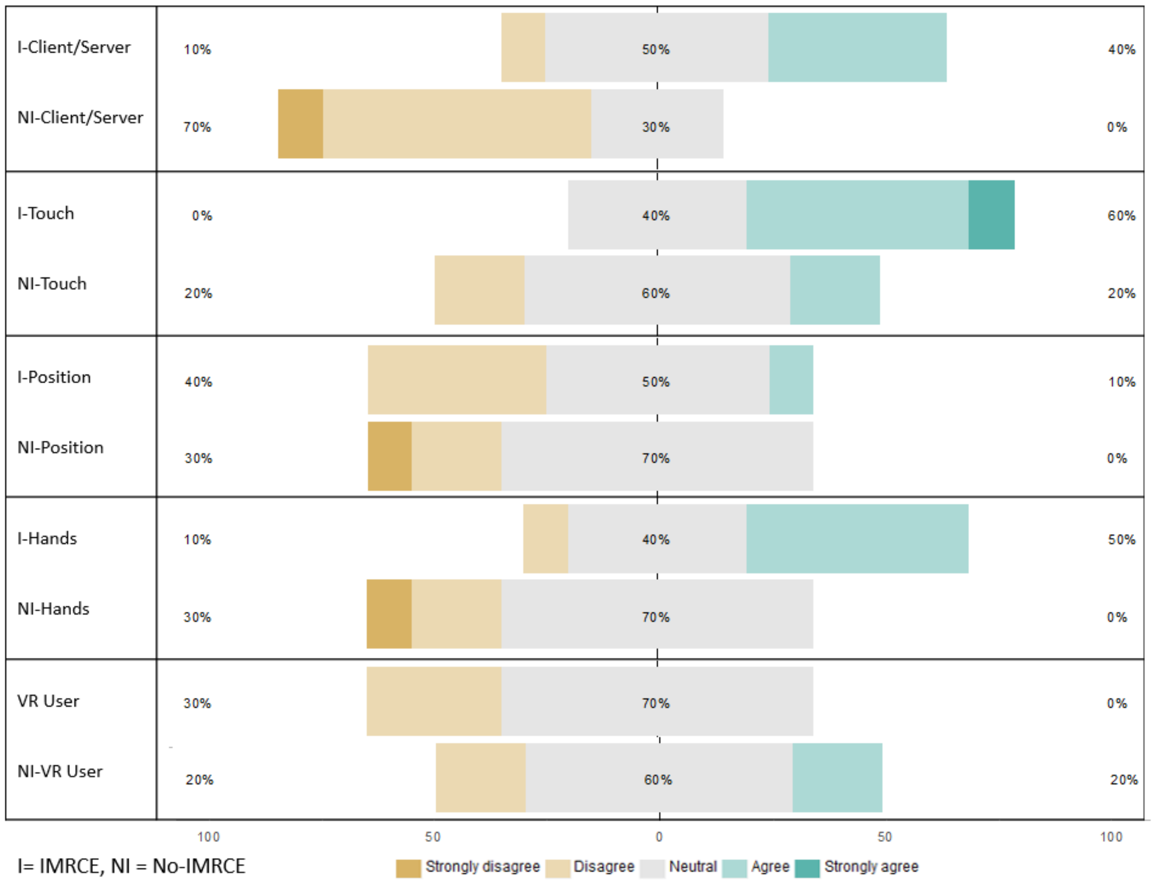

Figure 33: reported satisfaction with the results for each step in the IMRCE (I) and No-IMRCE (NI)conditions.

We also found a significant effect of condition on satisfaction with result for step 2 (creating the touch-based clients), Z = -1.933, p = 0.05. Participants were more satisfied under the IMRCE condition (M = 3.7, SD = 0.675) than the No-IMRCE condition (M = 3, SD = 0.666). Again, there was no significant difference in satisfaction with toolkit used for the same step.

We found no significant difference in expressed satisfaction with result or satisfaction with toolkit for step 3 (position tracking).

For step 4 (hand tracking), there was a significant effect of condition on the satisfaction with result, Z = -2.53, p = 0.011. Participants were more satisfied under IMRCE (M = 3.4, SD = 0.7) than No-IMRCE (M = 2.6, SD = 0.69). Again, there was no significant difference in satisfaction with toolkit used for the same step.

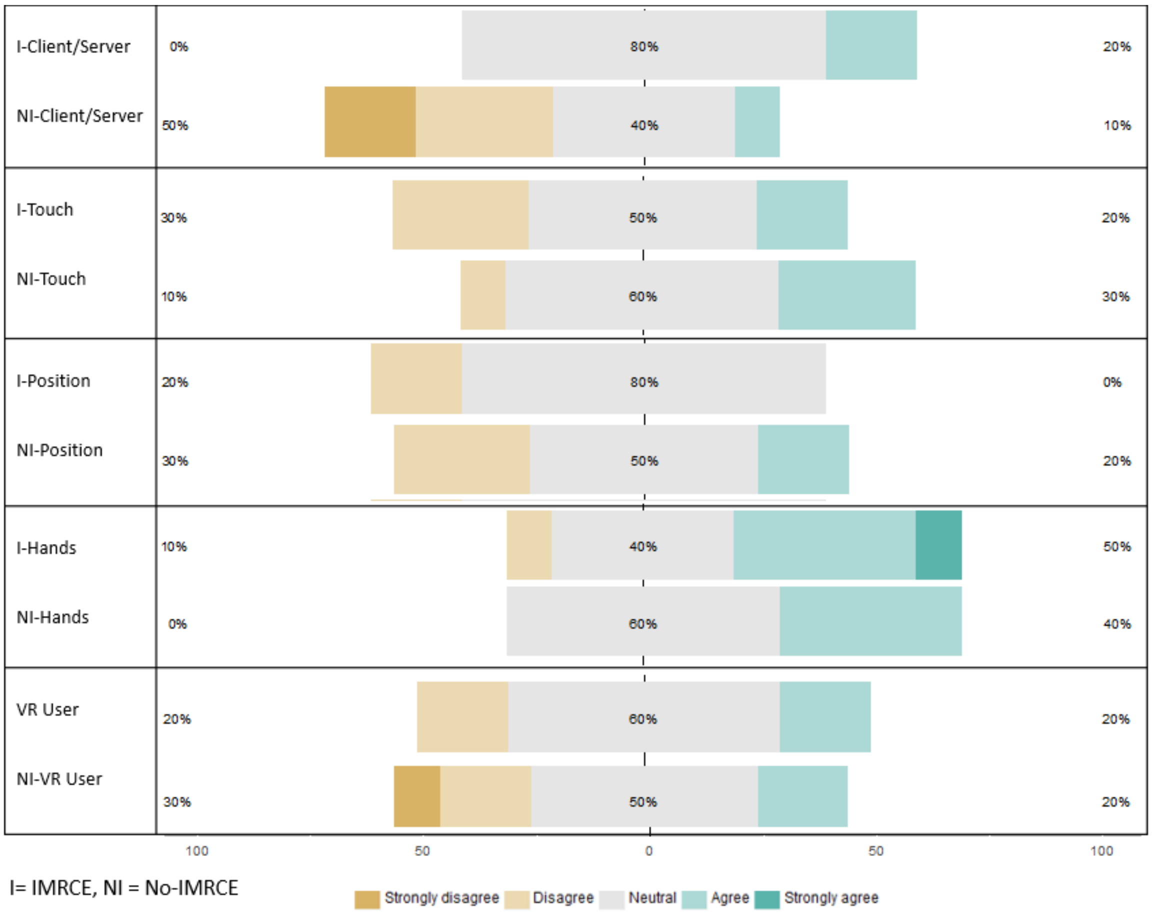

Figure 34: reported satisfaction with the toolkit used for each step in the IMRCE (I) and No-IMRCE (NI) conditions.

5.7 Finally, we found no significant difference in expressed satisfaction with result or satisfaction with toolkit for step 5 (immersive client).

Discussion

IMRCE is a Unity toolkit that was designed to help developers rapidly prototype a mixed reality collaborative environment with support for hand and position tracking, creating touch gestures and adding VR users. We used questionnaires, interview and usability analysis to evaluate the toolkit. The questionnaires focused on the usability of the IMRCE and user's preference for using IMRCE versus other approaches. The usability analysis focused on five parameters as outlined by outlined by Ledo et al. [166]. Time to finish each step of the task, level of competition, the number of lines of code, number of errors and number of questions from participants. Using the IMRCE toolkit almost halved the average time to develop a collaborative environment. The average number of questions and problems halved when developers used the IMRCE toolkit, and the number of lines coded with IMRCE on average was three times less than when developers did not use IMRCE. The results of questionnaires about the usability of IMRCE supports the results from the usability analysis of the study. However, the results of questionnaires about the users' preference for IMRCE did not provide enough evidence to show the IMRCE is preferred to other approaches. The contribution of this work is threefold: 1) A toolkit for rapid prototyping of an immersive mixed reality collaborative environment around physically-virtually mapped touch displays. 2) Providing support for synchronizing virtual hands for Leap sensors on distributed systems. 3) Providing support for creating client/server applications that can allow for collaboration on shared models.

5.7.5 Limitations and Future Directions

Our study provided invaluable feedback to improve the toolkit. We used A/B comparisons to evaluate IMRCE. However, we did not find any toolkit that provides all the support that IMRCE offers in one toolkit. Therefore, we could not compare the IMRCE with a competitive toolkit. We therefore decided to provide a list of toolkits and APIs which provide support equivalent to one part of IMRCE. Despite allotting more time to the toolkit overview in the No-IMRCE condition, this yielded two issues: 1) our participants spent some of their limited time to look through toolkits and APIs while they could have used this time on development. 2) participants were less likely to change to a new toolkit if they were not happy with their initial choice due to time limitations. However, all participants used the same API and library in steps three, four, and five in the No-IMRCE condition. They chose from two different libraries in the first step and three different APIs for the second step. For future studies (and similar toolkit studies), we suggest that if there is not a similar toolkit then it is preferable to assign one API for each step. Giving time for participants to actively use the given APIs and toolkits before assigning the task can help reduce participants' frustration and biases.

Calibration is one of limitations of IMRCE. Using different sensors requires initialization and calibration for proper use. To use the IMRCE position tracking and hand tracking features, researchers need to take extra steps to calibrate the location of sensors for the type of physical environment, and how their readings are translated into the shared 3D environment. Furthermore, when connected workspaces are structured differently, the mapping of tracked data to movement in the shared space is non-trivial: designers need to consider how movement in one space will be interpreted in the other space, and how it should be manifested in that space.

To help address these challenges, we are currently developing a new feature for IMRCE that helps collaborators map a specific physical environment and one or more shared interactive surfaces to the virtual collaborative environment and calibrate sensor mappings accordingly. We believe this will not only greatly facilitate rapid prototyping but can form the basis of a user-level configuration capability, allowing applications built using IMRCE to be deployed under different configurations.

Finally, we also note that body language and facial expressions are essential parameters and cues to communicate with other collaborators to both increase awareness and protect privacy. The IMRCE toolkit does not support facial expressions and we did not study them.

CHAPTER 6 DISCUSSION

Our work showed that asymmetric MR environments increase awareness and the feeling of co-presence if they provide cues for all collaborators to update their spatial mental maps of the environment accordingly. Our results provide evidence that using an immersive interface that accommodates 3D object viewing and manipulation and allows VR users to engage fully in the collaboration activities helps collaborators to increase their awareness and feeling of co-presence.

Our contributions in this thesis are as follows:

1. Generating a taxonomy of cues (including Responsive, communication-based, environmental and event-based cues)
2. Illustrating the primacy of cues that are closely tied to activities and the nature of tasks. In our studies participants payed little attention to the VR/projected environments as they mostly were focused on the study activities.
3. Uncovering privacy management challenges posed by physical-digital documents when used for mixed presence collaboration.
4. Showing that integrating VR into MP-MR environments allows developers to implement relaxed WYSIWIS interfaces for manipulating 3D objects.
5. Illustrating that IMRCE helps both remote and collocated collaborators maintain group awareness and have a stronger connection with their collaborators.
6. Development, experimental validation, and release of the IMRCE toolkit.

6.1 Impact and Importance of Context of Use

6.1.1 The Impact of Users' Prior Experience in MR-MP Environments

Our findings confirm Bødker [57] and McCarthy and Wright's [58] assertion that designers should consider the users' prior experience with collaborative environments to develop better user-centric ICT tools. Collaborators in both studies commented that they could work better in the environment with more experience. P29 (first study) said: "*This was the first time for me to use headset [HMD] and like using my hands. I think I will do better next time [manipulating 3D objects.*" P11 (second study) explained: "*I have a better idea about all this, so I am sure I can do better if there was a next time*". A solution for reducing the learning curve, allowing collaborators to more effectively cooperate in the environment, design an environment that facilitates existing collaborative behaviours.

Collaborators in a physical environment are naturally more cautious and alert to changes. For example, if someone joins/leaves the collaborative space, manipulates shared physical documents or stands behind us while we are holding sensitive documents, we immediately perceive the change and act in response to it. We also learned that using a cue that is different from the natural expectation (prior experience) of collaborators, showing a signal that has a different meaning in the physical environment, or using a cue that is not strong enough compared to similar cues in the physical environment can confuse collaborators and damage their sense of trust and co-presence. For instance, in the first study, participants expressed in the interview that the cue was not clear or strong enough to alert them that the remote collaborator could see the documents. P12 said: "*[the] cues were not alerting and enough. We were working on the questions when he walked behind us. We didn't notice when he was there we were focused on the list*." P5 explained: "*I think there should be a better way that tells us more about the remote person. I know he could see my hand, but I didn't know what he can really see. Like if he could see over my shoulder or he could see part of my cards*."

Participants (second study) preferred immersive virtual environments over the tabletop only condition. Symmetric WYSIWIS virtual environments provide support for remote collaborators to see themselves in an environment similar to the collocated location and have a similar field of view. Our results from both studies show that collaborators did not pay attention to the content of the VE and they were primarily focused on the tasks. However, participants in the second study had many positive comments about the VE including the advantage of having a VE similar to the physical environments that facilitates activities that mirror experiences in the physical environment. Previous experience and seeing a VE similar to the physical environment allowed collaborators to consciously or unconsciously feel more comfortable. Using an immersive VE helped collaborators to build their mental map and receive different types of cues more intuitively.

IMRCE toolkit supports both spatial and touch gestures for working with virtual objects that are familiar for collaborators while they had experienced before in their daily life activities. For example, developers can use the IMRCE toolkit to develop spatial gestures such as grabbing/releasing, resizing, throwing and catching or touch gestures such as zooming, scaling, rotation and translating.

6.1.2 Impact of the Nature of the Task on Awareness and Presence

The results of our studies showed that the nature of the activities and the information being exchanged (sensitivity) have an impact on awareness, privacy and presence. Some information can be considered more sensitive in comparison to others. For example, personal information or classified information of a company are more sensitive than a friendly game. Collaborators are more cautious when they are working on personal and sensitive information in comparison to situations in which they are working or non-sensetive information. P13 in the first study said: "*I'm sharing my personal information and I have the feeling that…other people might hear this information [in the circumambient condition].*" 13/32 collaborators in the first study, explained that it was not necessary to have a projected café when they were working on confidential documents (bills). However, they were ambivalent (8/13) or in favour of having the circumambient environment for non-sensitive collaboration (5/13). P29 in the first study expressed: "*it is good when you* *want to socialize but for sharing information, or when you want to get down to business, I think you don't need this [circumambient condition] ...just [the] front view.*" P29 said: "*it is ok, I didn't feel anything, because it was a game, it wasn't something that I would be asking him about his personal life*."

Our results affirm that our results underline the value of task-specific interface design for collaborative systems. For example, SharedTable [60] was designed for communication between separated parents and their children, a sensitive and private collaboration activity. In this example, the main objective in conversation and the accuracy of any interaction is less important. Virtual Wall [61] allows for self-defined privacy and security rules, and UbiTable [59] provides three levels of security access to the participants for sharing information. Virtual Wall is an example of a collaborative environment that is suitable for collaboration between people when they require a different level of access to information, or they need to share part of their data (similar to bill sharing activity in our first study). Our first study was a situation wherein collaborators needed to share and protect information. Our second study was focused on group work and encouraged collaborators to use the environment to share as much information (related to the activity) as possible. We designed our second study to help collaborators with 3D object manipulation activities and help collaborators to increase their awareness and strengthen their feeling of being co-present with their counterparts.

In the second study, the tasks were primarily focused on 3D object manipulation and encouraged collaboration. The 3D immersive environment is suited to 3D object manipulations and it has the advantage of replicating physical 3D manipulations [191]. 3D object manipulation tasks allow collaborators to use mid-air gestures in immersive VE for natural manipulation and simulate interactions with physical objects. We looked at other 3D manipulation tasks such as the bicycle repair task [158] and the chair assembly task [159] before designing our tasks. The immersive environment helped collaborators to interact with 3D objects in a similar way to physical objects partly due to the type of task we chose for the study. P41 said: "*using VR can be a lot quicker and more natural like you* *just move and so things*," P22 explained: "*when I was in VR, I could move my head to look under the model… I felt like in VR it was just more natural.*"

In the first study, we showed that building a mental model of the environment and receiving continuous cues to update one's metal map plays an important rule in maintaining group awareness and helping collaborators to manage their privacy. Designers of MP-MR environments need to pay attention to prioritise cues related to collaborator actions, and ensure that cues work together rather than conflict. Parkin et al. [192] describes that there are conflicts between the demands of privacy and collaboration in collaborative environments and during performing different activities. Patil and Lai [193] explained that" utilizing grouping mechanisms to balance privacy control with configuration burden, and argue for increased system transparency to build trust."

6.2 Design Elements of MR-MP Environments

6.2.1 Employing Cues in MR-MP Environments

In our research we employed cues to address three characteristics of group awareness synthesized from that Adams et al. [36], Robinson [37] and Endsley [38] knowledge about the state of an environment, updating awareness following changes in the environment and maintaining awareness through interaction and exploration within the collaborative environment. We designed our environment, so it can provide a continual stream of cues to help collaborators update their spatial and mental maps. As Dix [53] explained in his model, there are three spaces in an MR collaborative environment: the physical environment, positioning relative to physical and virtual space, and the virtual environment. Our collaborative environments in both studies provided cues to give information about all three aspects.

When designing the cues, we also considered consequential communication [42]. Baker et al. [42] divided consequential communication into three categories: actions coupled with the workspace, actions coupled with conversation and intentional communication. Action coupled with workspace allow a collaborator to acquire information by observing other collaborators' behaviours and actions. These actions are a source of information that increases collaborators' group awareness. The use of avatars in our first study and position indicators in our second study to visualize the location of other collaborators around the tabletop are examples of "actions coupled with the workspace." Intentional communication refers to visual actions and gestures that collaborators make to enhance verbal communication. Hand movements (second study) or head nodding and waving by the remote avatar (first study) are examples of intentional communication. Finally, action coupled with conversation are cues that result from partners' actions and help collaborators continuously adjust their verbal behaviours [43]. For example, visualizing hand gestures when collaborators interact with 3D objects is an instance of "actions coupled with conversation" and intentional communication. Clear and informative cues are required for effective consequential communication. We categorized cues into four subcategories: responsive cues, environmental cues, event-based cues and communication-based cues.

These categories are also in harmony with the divisions of consequential communication. Communication-based cues provide signals that fall under intentional communication and actions coupled with conversation. For example, the remote collaborator's comments (intentional communication) on collocated collaborator's dress or actions strongly reinforced the idea that they were visible. The VR user pointing to the 3D parts of an engine during the Illustration task (communication based-cues) is another example of actions coupled with workspace. Event-based cues and environmental cues fall under actions coupled with workspace; these cues provide information for collaborators to update their mental map about the MR-MP environment. For example, using an ambient sound system to hear footsteps (environmental cue) and the direction that the remote collaborator is moving in (first study), using a model of the collocated location in the VE as reference points or showing a position indicator if someone joined around the shared space (e.g. tabletop) in the second study (event-based cues) are both examples of actions coupled with workspace. Responsive cues are signals that happen in response to collaborators' actions within the workspace; therefore, this category falls under actions coupled with workspace. Examples of this are when a collaborator grabs/touches a 3D item, its color becomes brighter (second study) or when a collaborator put their cards on the table, the digital version of the cards will appear on the tabletop (first study). These categories are not absolute, and it is possible that a cue overlaps several different categories and does not fit to just one category.

The results of both studies showed that collaborators are continuously looking for cues in relation to the collaborative environment, other collaborators and the tasks. We observed that collaborators acted with more confidence and trust when they could maintain their awareness by receiving cues and when they understood the rules for protecting their privacy, such as hiding the markers in the first study. Our results are similar to the conclusion of Chin et al. [55] and Goecks et al. [56] that encouraging and assisting collaborators to follow specific rules and actions helps them to protect their privacy. In the first study, collaborators were able to use cues to maintain their awareness and manage their privacy by applying their physical privacy behaviors to the digital environment. For example, seeing the digital shadow of a document on the tabletop alerted the collaborator to hide the information by tilting the document or covering the marker on the document with their hand to hide the document from the camera tracker. Collaborators also discussed and generated rules with their partners to manage their privacy better. For example, during the guessing game, participants asked the guesser to stay far from the Tabletop when they were working on the list of questions. Our findings also provide support for Palen and Dourish's [142] model of privacy in which privacy constraints formed through interaction with other collaborators plays a role in establishing or enhancing presence by providing consequential communication information that can help collaborators to update their mental map in the three spaces of Dix's model. For example, showing the location of other collaborators around the shared space, visualizing hand gestures, using avatar or position indicators to give a sense of collaborative location around the shared space or using a virtual model of physical location for the VR users help collaborators to increase their feeling of copresence.

The IMRCE toolkit integrated cues from all four subcategories to allow other developers to harness their utility in their design. For example, developers can easily add hand tracking, position tracking to their VR or touch screen applications.

6.2.2 Manipulation of 3D objects in MR-MP Environments using Touch and Hand Tracking

Inspired by Sticky tools [78] and DS3 [80], we developed a touchscreen application that allowed users to use one finger to move a 3D object, two fingers to change its orientation (rotating in any direction), and pinching out with three fingers for scaling up. We did not evaluate the usability of the touch application and the RST gestures. However, we did not find any evidence (self-reports and observation) of difficulties or problems with performing the touch gestures.

Using hand tracking technology to map collaborator's hands to their virtual embodiment to inside the VE help collaborators to have a natural interaction with 3D objects. The theory of the perceptual structure of visual information [74] explains that a multi-dimensional object has an integral and separable structure [75]. Human fingers have separable DOF [76] and that results in a mismatch between the nature of 3D manipulation as integral tasks while working on 2D interfaces [77]. Manipulating 3D objects in the VR environment (virtual controls) allows collaborators to make a natural mapping between these two different structures (fingers with separable DOF and 3D objection manipulation with integral structure).

Using 2D hand embodiments may be sufficient for working on 2D documents and 3D models on a touchscreen. However, using 3D hand embodiments allows for a realistic and familiar experiences for collaborators. Laviola and Keef [191] discussed that using hand tracking and gestures in VEs allows users to perform a complex action directly on the virtual object, while complex actions require multiple inputs for 2D interface users to archive the same results. We chose to use virtual controls [194] or direct interaction via hand tracking and gesture recognition for 3D object manipulation within the VE. However, a lack of haptic feedback could frustrate and confuse collaborators when interacting with 3D objects [194]. Using a hand controller could provide basic haptic feedback for the collaborators and prevent fatigue from grasping empty air. However, using hand tracking sensors (i.e. LED tracker like Leap motion sensors) allows collaborators to freely use their hands for gestural communication and apply their natural hand use to the VR environment.

P51 expressed: "*I could grab the object and turn it over. VR was more natural to work with those models.*"

The IMRCE toolkit helps developers to design environments that integrate hand tracking and position tracking systems. Hand tracking systems allow a developer to provide an opportunity for users to work with virtual objects in a similar way of working with physical objects. The IMRCE toolkit also allows a developer to create an immersive environment that can be a replica of a physical collaborative environment.

6.2.3 Strict versus Relaxed WYSIWIS

In the first study, we focused on collocated collaborators, and we did not use a participant as a remote collaborator. The remote collaborator was one of our researchers. However, we told our participants that the remote collaborator is a participant that is connected from another location. Our first study did not fit neatly under WYSYWIS or WYSINWIS [65] interfaces [63]. However, it had more characteristics of a WYSINWIS interface. The collocated collaborators used both physical and digital documents while the remote collaborator used only a digital version of materials. At the same time, all collaborators could see the same information on the shared tabletop. Collocated collaborators did not have a view of the remote location, but the remote collaborator had a video feed from the collocated location. The system we used in the first study was similar to the CALVIN method [66] (notation of Mortals and Deities) where remote had an egocentric view. As explained earlier, our results and observations showed that collocated collaborators had difficulty with trusting the environment and they were curious about how the remote collaborator uses the system for collaboration, how they are presented in the eye of the remote collaborator, if the remote collaborators were alone, and if they could use any additional tools. Yang [71] and Schafer and Bowman [70] also discussed that having different views in remote collaboration can cause difficulties in discussing and coordinating group activities. For example, collocated collaborators used physical mockup bills for the Bill Sharing activity. We asked participants to keep the bills in their folder when they were not using them. In multiple cases, participants left their bills out of the folder so that they were visible and easy to read for their collocated partner, but remote collaborators could not see the exposed bills if a collocated participant stood between the camera and the documents. Another example involved the Card Game. Some participants commented that they could not see any of the remote participant's cards until they shared the cards with them, but the remote collaborator could walk around them and see their hands (cards).

Our second study was an example of a relaxed WYSIWIS interface [62]. Our results suggest that the relaxed WYSIWIS VR interface encouraged participation from the remote collaborator more so than the strict WYSIWIS tabletop configuration. This is an important finding as there are several reasons why this might not be the case. Provenzano et al. highlight the importance of understanding and sharing perspective during collaborative work involving 3D objects [72]. In our study, participants often relied on their understanding of the interfaces being used at both locations to coordinate action but did not explicitly require shared perspective during tasks. In fact, participants preferred the Hover condition in many circumstances, which foregoes the shared top-down perspective for greater freedom of 3D object manipulation. The Hover and Fishtank interfaces both has advantages. We found that more participants preferred the Hover condition overall. Reasons include that it facilitated interaction: "*when it is right in front of you it is easier to like to reach out and grab*" (P21) and viewed 3D objects: "*You could just bring it up to your eyes and see what's underneath the object*."(P47): "*....you can see more dimension of the objects*."(P31). We also found a significant increase in interaction when using Hover for the Illustration tasks. Participants were generally more animated and expressive when describing the model's operation: "*It was much more useful especially because you know when he was describing the different parts and components of the turbine. I knew he's going to move to the parts and he's going to explain that one"*(P45).

Advantages of the Fishtank interface include a well-defined workspace: "*I liked Looking into the box [Fishtank] ...I felt like that I can reach in and do things.*" (P17), ergonomics: "*I preferred the time it was deeper in [Fishtank] I think because I'm not very tall and so [I like] having things [that] are deeper. It felt like I could reach deeper than go further out."* (P43) and shared perspective: "*I think I was comfortable with what was happening. I had* *a good understanding of everybody in the room, who was talking who was louder*" (P26). While these are important qualitative differences, we did not find significant differences between the Hover and Fishtank conditions for self-reported and coded measures of mutual awareness or exclusion.

In the first study, we explained the study to the collocated collaborators, and they presumed that the remote collaborator was using a virtual environment and a virtual tabletop that was connected to the physical tabletop at the collocated location. We also explained that the remote collaborators only could see documents that were tracked by the camera, and if collocated collaborators covered the markers, then the remote collaborator could not see the digital version of those documents. However, it was still possible that the remote collaborator could look at the documents by way of the cameras that were installed at the corners of the room. We wanted collocated collaborators to have the assumptions that the remote collaborator was only seeing the information that the collocated collaborators were sharing on the physical tabletop and vice versa and that the remote collaborator could see the collocated collaborators' documents by walking around them in the virtual environment (unless the physical documents were concealed). We learned that participants could not form a coherent mental map of such an environment immediately and they required practice and experience. One reason for this could be that we did not strictly follow a protocol for WYSIWIS or WYSINWIS. In the second study, we followed WYSIWIS protocol, and we ensured that all collaborators knew what their counterpart collaborators could see. In addition, our tasks involved only digital objects rather than physical documents or objects. Using a physical tabletop at the both remote and collcaoted locations was strict WYSIWIS and VR was relaxed WYSIWIS. We learned that collaborators could use either the physical tabletop or VR to work with their counterpart collaborators on the given tasks without being worried that their counterparts collaborators were seeing different, extra or less information. However, we recognize that this model is not always applicable and that there are situations in which collaborators need to look at different amounts of data (i.e. working on classified information) or collaborators need to work on both physical and digital documents.

Developers can easily prototype collaborative environments that support both strict and relaxed WYSIWIS. For example, our second study was successful in providing a WYSIWIS collaborative environment. IMRCE can also allow collaborators to design a WYSINWIS application that has, for example, a subjective viewpoint for the users or asymmetric information sharing. We believe it is worth exploring a situation in which collaborators work on tasks with a different level of access to information (WYSINWIS) and also a situation in which physical objects become part of the collaboration activities. For example, a study could be conducted that is similar to our first study but allows the remote collaborators to use HMD and collocated collaborators to interact with the touch tabletop.

Overall, the results provide evidence that relaxing WYSIWIS to permit freer movement of 3D objects relative to the remote collaborator's perspective did not adversely affect performance or self-reported measures of awareness and co-presence.

6.3 Internal Elements of MR-MP Environments

6.3.1 The Importance of Updating the Mental Map for Efficient Collaboration

In the first study, collocated collaborators needed to learn how to protect their privacy in a fused environment. Collaborators had to experience a complicated process to build their mental model even after the moderator's explanation of the environment. For example, collaborators had to try and test the environment to learn how their physical documents were mapped to the digital version. Collaborators had to repeat and revise their experience multiple times to understand how to effectively use their physical privacy behaviors to work within in a fused environment. Collaborators asked many questions to learn how their actions were manifested in the virtual world and if they needed to do anything specific to protect their documents. Our observations show that collaborators can work efficiently in an MP collaborative environment and translate their physical privacy behaviours into virtual actions for managing their privacy if they could update their spatial mental map and spatial awareness.

Hindmarsh et al. [87] explained that a lack of experience in working in MP environments makes it challenging for collaborators to manage their privacy simultaneously in both physical and virtual environments. Using technology has an impact on the physical behaviour of collaborators to the extent that collaborators and their actions are not clearly secure in either the physical or virtual spaces. P5 *"I didn't feel as secure as [when] we played the games, On the last bill I had to hide purchasing form the Best Buy [name of a store] and when I put my paper down, or start sliding the paper [shield] over; I had to instantly have my hand covering the marker, but I may actually show something that I don't want him to see."* It is also essential to have a mechanism that notifies collaborators when they accidentally expose private documents. We observed many unexpected accidental exposures during the first study and it was not apparent that collocated collaborators noticed the breaches.

In the second study, collocated collaborators used a Tabletop interface in all conditions and they enjoyed the same type of cues as the remote collaborator. The second study required little effort vis-à-vis forming, testing and revising mental models. The collocated collaborators used a physical touch tabletop and they did not need to learn how to transfer their actions to a digital environment. Also, the hand and position tracking sensors at the collocated location did not require any interaction from collaborators. The hand tracking sensors at the collocated location were solely for tracking the gestures and positions of hands and not for manipulating 3D objects. Another difference between the first and second study in terms of building a mental map was the need to establish common ground regarding what each collaborator could see and do. Building a common ground was significantly easier in the second study due to the study protocol (i.e. all participants were made aware of the interfaces in use on both sides). The only training that collocated collaborators required was about how to work with the touch tabletop to perform RST gestures, in addition to an explanation of how virtual hand and position indicators were represented on the physical tabletop.

Results of studies such as [44][45][46] show that spatial awareness is a necessary element for efficient performance while performing spatial tasks. The results of both our studies showed that collaborators could build a mental map to effectively use MP environments to perform spatial tasks (second study) and transfer their physical privacy behaviours into the fused environment (first study). These results showed that MR environments could help collaborators to update the mental map and increase their special awareness .

Remote collaborators were fully immersed in a VE (during VR conditions) that was a model of the collocated location. Using hand and position tracking and a fully immersive environment transported remote collaborators to a VE that mimicked the physical environment and allowed the VR users to use their natural movements within the VE (head and hand position and orientation, body movement and hand gestures all mapped and manifested to the VE). Using a fully immersed VE and having all tasks within the VE helped VR users to collaborate without any need to create a mind map of how physical items are connected to virtual items. In other words, similar to in our first study, if the activities are fused between physical and virtual environments, then there should be a mapping between the VE and the physical environment and the same mapping should be established in the collaborators' mind. Removing the mental load of dealing with both physical and virtual environments helped collaborators to update their spatial map faster and more efficiently. Also, using a model of the collected location instead of a hypothetical location created a feeling of co-presence in some of the remote collaborators. P53 mentioned: *"It's nice to have like at least something to feel like you're in a room with someone."* P39 explained*: "I like the [virtual] room. It was like the real environment [collocated location]. So, I knew that I could look around like OK computer is there I know where that is [using the items in the environment as a reference point for collaboration]."*

Again, our results showed that participants significantly preferred MR environments over only tabletop displays for collaboration. Asymmetric MR environments increase awareness and the feeling of co-presence if they can help collaborators to update their spatial mental maps of the environment. However, if the environment fails to update the mental map of collaborators, then it will have a negative impact on the actions of collaborators and their feeling of co-presence. Mortensen at al.'s [88] observational study also found that that co-presence and task performance are significantly and positively correlated with each other.

Some of our collaborators mentioned that they preferred the 2D interface (Tabletop) for activists that do not require 3D manipulation such as working on 2D documents.

6.3.2 Awareness and presence

Group awareness and co-presence are often difficult to analyze. Typically, a combination of direct and indirect measures is used to assess these qualities. CSCW research has long emphasized interaction with shared objects as a basic primitive attribute of collaborative systems (e.g. Hornecker [134] and Pinell and Gutwin [135]), and such interactions can offer insights into a collaborator's workspace awareness [195].

In addition to task performance, we evaluated the second study using several indicators of group awareness and sense of co-presence, specifically, the nature and distribution of 3D object interaction, the impact of hand embodiments and position indicators on communication and awareness, differences in communication and coordination between interface conditions, attention allocation and feelings of exclusion. In the first study, we used questionnaires to ask collaborators if the interfaces helped them to increase their awareness in relation to their remote counterpart.

Our findings align with those from research such as Almost Touching [82], Media Spaces [26] and Carpeno [6] indicating that using an MR interface is successful in providing information to help them maintain their awareness, feeling of co-presence and have a richer engagement in the activities. In particular, studies like Lighthouse [85] and Pinho's study on Cooperative manipulation refers [86] showed that using an immersive VE helps collaborators to increase performance and engagement in manipulation scenarios and share experience during collaboration.

Witmer and Singer [47] stated that to experience presence, collaborators should have both involvement and immersion. Immersion in VE is a psychological state that is defined by perceiving yourself to be surrounded, included in, and communicating with an environment that provides a constant source of stimuli and experiences. Involvement in VE depends on directing attention towards a coherent set of VE stimuli [47].

Our systems provided immersion for the participants in both studies. Collocated participants in the first study were immersed in a circumambient environment (projected cafe) and remote participants in the second study (VR conditions) were fully immersed in a virtual model of the collocated location. The circumambient environment provided an immersive visualization of the shared environment which was similar to a cave. Collocated collaborators in the first study worked around the physical tabletop, and the projected café was not the primary means of interaction. In the second study, in addition to presenting the collocated location environment for the VR users, the VE was the only means for remote collaborators to interact with the shared objects (VR interfaces).

Participants did not consider the circumambient environment as a necessary component as they were mostly focused on the tasks that were happening in the mapped physical-virtual environment. This lack of interest was partly due to using a hypothetical VE. In general, participants did not develop a sense that the physical and virtual surroundings were fused. However, they were curious about the environment and showed interest in the system and mapping the physical documents into digital documents or manifesting their actions into digital actions. The results of the second study show that regardless of their location (remote or collocated), participants significantly preferred using the VR interfaces over the tabletop interface and it increased awareness and the feeling of co-presence in collaborators. One reason behind this preference could be the explanation of Witmer and Singer [47] that collaborators should have involvement and immersion to experience presence. We used an immersive VR environment that was a model of the collocated location (relaxed WYSIWIS). Remote collaborators were fully immersed in this environment (VR interface) and they could see themselves in a similar environment to their counterparts. Mine [194] and Viola and Keefe [191] stated that VEs can represent spatial information in three dimensions and replicate the real world. Schubert [48] explained that the construction of a mental model and attention allocation are necessary for experiencing the feeling of presence. Following Dix's [53] model of mental mapping, the immersive environment helped remote collaborators to update their spatial mental map in relation to the collocated collaborators' environment. However, we did not find enough evidence to confirm that a replica of the collocated location was the one the reason for remote collaborators preference for VR.

Following Schubert's [48] analysis of presence, we added hand embodiment and position tracking as new cues in the second study to provide additional sources of consequential communication and help collaborators to pay attention to the ongoing activities and follow group dynamics. Hand and/or facial embodiments help to enhance co-presence by providing more natural communication between remote locations [81], [102], [6].

Most participants found the position tracking significantly helpful when they were using VR interfaces. Some participants believed that having hand embodiments was sufficient for understanding the location of collaborators and there was no need for body position tracking. P31 said: "*I didn't pay attention to positions but I paid attention to the position of hands.*" P29 expressed: "*I think hands are more useful than the positions. If the hand is already there. I already know what they are doing remotely. It doesn't matter where they are.*" This demonstrates that collaborators want to know the position of their counterparts (using the position of the hand or the position indicators) and position is a strong consequential communication cue for collaborators to maintain their group awareness. P48 said: "*Very helpful to have the position of two people with you. I could coordinate better with them.*" P10 said: "*Having the sense of like where people were around the table. I guess it just made me also feel like I was less excluded because I was in the other room, so it reminds me kind of the presence of the other people even though they're not in the room with you." Other quotes, including the one about the effect of seeing the virtual room, the effect on co-presence of the position indicator*."

We used a virtual café in the first study which acted as a hypothetical place for the meeting location. Our observations and the results of an interview show that collaborators paid attention to the interface when they thought that it was a proxy for a physical café. Collaborators were interested in the circumambient condition with the assumption that the remote collaborator was in a café and they expressed that they experienced the feeling of being co-present with the remote collaborator. P30 said: "*I think the whole view is cool. It* *feels like you are in the location with the person."* P29 also remarked: "*I think, when we could see an entire cafe, it makes you feel closer to the person regardless of the physical distance between you, so if I want to share something with somebody who is not necessary for the same area, this will make it more real."* In other words, some of the collocated collaborators updated their mental map with the assumption that virtual cafe was a proxy to a physical café.

When participants understood that the virtual café was not a proxy to a physical café, then they started asking questions about their remote counterpart to understand how they are using the system and what they can see. We observed that 10/16 participants did not pay attention to the environment or moving avatars and only concentrated on the tasks. The collocated collaborator also complained that they did not have enough information about the parameters of the remote collaborator's workspace. For example, collocated collaborators wanted to know if the remote collaborator was alone and if they had access to external sources of information such as the Internet. This concern arose in the guessing game and the bill sharing activities. P5 said: "*I know this was a game. But in the real world, I like to know if there is anyone with the remote person that can see what I am sharing on the table*." P6 expressed: "*She [the remote player] could see us but we couldn't see her or if someone is with her*."

6.4 IMRCE Toolkit

We found different toolkits for developing collaborative environments such as TwinSpace [54], SecSpace [32] and MAUI [94]. We did not find any toolkit that could help us to build our system. Therefore, we used different APIs and libraries to develop the MR system we needed. That motivated us to combine the APIs, libraries and algorithms we used and offer a comprehensive toolkit that can help developers to prototype an immersive mixed reality collaborative environment rapidly.

The usability analysis of IMRCE provides evidence that IMRCE makes a significant improvement in rapid prototyping of MR-MP collaborative environments on the Unity platform. The five parameters that we investigated to evaluate the usability of IMRCE were all in favour of IMRCE. The time to develop the application was a significant factor in our design and IMRCE significantly reduced it in comparison to the No-IMRCE condition. Questionnaire results showed that participants were also generally more satisfied with their results when using IMRCE, even though they did not prefer to use it over the alternative libraries. Interview data shows that participants had difficulties using IMRCE, in part because this was the first time participants were using it, and also because we provided very little written instruction. P5 said: "*You should use better names for the prefabs.*" P3 said: "*I was sometimes getting confused something like a 'Wiki,' or an API style guide can help a lot*." Or P2 explained: "*I liked the toolkit, but I also need to work with it in the longer period and on more projects.*" Adding position tracking to the application required participants to scale the results of the position tracking system for their application. For example, the movement around the physical tabletop must be scaled and mapped to the size of the virtual tabletop. Finding the right scale and positions was a challenge that IMRCE does not provide support for in its current form. When reviewing the nature of participant questions and the kinds of problems seen in the prototypes, we found that 35% of the questions and 30% of problems were related to the position tracking step.

Developers can use IMRCE for developing MR-MP applications that can run on various devices and operating systems. Choosing Unity to develop IMRCE also allowed us to use UNET as an efficient network protocol that is designed to support online games. By taking advantage of UNET, IMRCE offers powerful network communication between different clients and the server. IMRCE can map differently sized touchscreens to each other and maps touchscreens to a 3D environment for real-time collaboration. In summary, IMRCE builds on the native capabilities of a modern 3D game development platform, encapsulating features such as hand and position tracking, flexible mapping, network support and VR support altogether to offer a lightweight toolkit for rapidly prototyping MR-MP environments.

6.5 Limitations and Possible Biases

In our second study, hand embodiments of collocated collaborators were always presented relative to the tabletop surface, regardless of the interface condition. This meant that if 3D objects were raised/lowered significantly from the surface in either VR condition, pointing gestures may have been difficult to understand. While no participants described this difficulty, adaptive remapping of embodiments relative to objects of reference is interesting and valuable future work.

A collocated participant could have better working opportunities in comparison to the remote participant when they were working on the 3D model on the virtual tabletop because the virtual tabletop was a simulated program and it was not as robust as a real physical tabletop. For example, performing the hand gestures (RTS) on a physical touch tabletop are more familiar and well-developed skills. Also, working on a touch display is a familiar practice for many of the participants. Collocated participants could freely walk around the physical tabletop and remote collaborators were not restricted in their movement around the virtual tabletop. However, the remote collaborators were more cautious and less comfortable walking around while they were wearing an HMD.

Using an HMD could be more challenging and frustrating because users needed to tolerate possible dizziness and motion sickness from the HMD and hand fatigue. Participants at the collocated location did not need to pay attention to the hand detection sensors (installed on the physical tabletop), but at the remote location, a remote participant needed to pay more attention to the sensor (installed on the HMD) while she selected a 3D model. The remote participant performed the gestures on the tabletop; therefore, there was no need to pay excessive attention to the hand detection sensors.

6.6 Future Directions

Body language and facial expressions are essential parameters and cues to communicate with other collaborators to both increase awareness and protect privacy. Eye tracking provides another source of empirical data to support the validity of self-reported awareness findings [113], and gaze can be manifested in a future version of the system as another cue supporting coordination [196]. Veregaal [196] explains that by using gaze direction, we can say "who is talking to whom, and who is talking about what." The IMRCE toolkit does not support facial expressions and gazes tracking at this time, and we did not study them.

We suggest that future work should consider including body language, facial expressions and gaze tracking in their studies.

HMDs are becoming more popular and accessible for public use. Studying collaboration between collaborators while more than one collaborator wears an HMD could reveal new angles for mixed reality collaborative environments. In our studies, we did not consider more than one VR user due since we did not want to add an additional layer of complexity to the study.

We did not consider augmented reality (AR) technologies in our studies. Future research can consider the impact of using AR and VR to connect collaborators for mixed presence collaboration involving 3D objects. For example, collocated collaborators can use AR HMDs while remote collaborators use VR HMDs, permitting a more symmetric interface for 3D object manipulation. The use of AR in mixed reality collaboration and its impact on awareness and co-presence are important areas for investigation.

Another interesting possible research direction can be studying the impact of using fused environment in immersive virtual environments its impact on awareness and co-presence. For example, adding a video stream of the counterpart location to the immersive environment.

CHAPTER 7 CONCLUSION

Mixed reality spaces can give a sense of co-presence during work involving a mix of collocated and remote collaborators by placing virtual content in multiple spaces simultaneously [13][14][15]. If a mixed reality system is immersive, collaborators can additionally benefit from increased situational and peripheral awareness [26]. For example, information can be gained about collaborators who are joining or leaving the collaborative space, and the relative position of shared work resources and of collaborators in the space can be monitored. Our investigation of awareness, privacy and presence in mixed reality collaborative environments provided us with insights for designing and working with such environments.

Designers must ensure that cues clearly convey the consequences of collaborators actions to the instigator to increase collaborators' group awareness and better privacy management. Collaborators enter a collaborative environment with a mental model that has been built based on collaborators' previous experience with collaborative environment and activities. However, they regularly update this mental model by examining different cues that are provided in the current environment that they are using. Participants attitudes also have a bearing on building the mental model. Some participants seek to acquire information about the virtual space and its relation to the physical space. Other participants are less observant of the cues, focusing on completing the activities and missing indications that could help them to increase their awareness toward other participants or manage their privacy. Cues should be informative and visible enough to influence the action of participants with different attitudes.

Our finding aligned with Dix et al.'s [53] definition of the three spaces in mixed presence environments. Collaborators are interested in learning how physical actions such as hand gestures and physical movements are manifested in the virtual world and presented to their counterpart collaborators (1-the relation between physical and virtual spaces). Collaborators also expressed significant interest in acquiring knowledge about collaboration in the virtual environment and the representation of their actions at the counterpart location (2-virtual space). And finally, collaborators looked for details about their counterpart collaborator's physical environment (3-physical space). Our results show that providing explicit visibility about how collaborative actions (including privacy-related actions) are translated across physical and virtual environments will help mental model formation about the collaborative environment, which is necessary to build trust especially when sharing sensitive information.

We identified four types of cues that collocated collaborators use to construct a mental model: responsive cues, environmental cues, event-based cues and communication-based cues. Having cues from all these four categories help collaborators to understand the environment and increase their group awareness and the feeling of co-presence with their counterpart collaborators. The cues that are not in the collaborators' field of view or are out of the shared space range are less likely to be noticed by collaborators especially when they are focused on the collaboration tasks.

We present results from a comparative study evaluating techniques for connecting remote collaborators to a collocated work environment for tasks involving 3D object manipulation. In all interface conditions hand embodiments, position indicators, audio and a synchronized 3D work environment promoted awareness of collaborator actions and intent. We compare a strict WYSIWIS dual tabletop configuration against two relaxed WYSIWIS configurations in which collocated pairs use a tabletop while a remote collaborator connects to a replica of the collocated environment in VR. The Fishtank interface shares the bird's eye tabletop perspective while adding depth, and the Hover interface provides the remote collaborator with a head-on perspective of the shared 3D workspace. Our results provide strong evidence that the VR conditions enhanced awareness and co-presence over the symmetric tabletop condition for both collocated and remote collaborators. We do not find pronounced differences between the Hover and Fishtank field of view in their impact on awareness or sense of co-presence, but find that each has strengths and weaknesses, indicating that designers have both flexibility in mapping remote and collocated experiences, and trade-offs to consider when creating mixed reality configurations for mixed presence collaboration.

We created the IMRCE toolkit, which brings different APIs and libraries together to allow developers to rapidly prototype an immersive mixed reality collaborative environment with the support of hand tracking, position tracking and collaboration on touch displays and within VR environments. The IMRCE toolkit significantly reduces developing time and the number of coded lines in comparison to working with APIs and libraries separately.

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APPENDIX A – ETHIC DOCUMENTS FOR THE USABLE PRIVACY AND SECURITY FOR MIXED REALITY COLLABORATIVE

Dalhousie Ethic Board's Letter of Approval

DALHOUSIE UNIVERSITY
Inspiring Minds

Social Sciences & Humanities Research Ethics Board
Letter of Approval

April 11, 2013

Ms Bonnie MacKay
Computer Science\Computer Science

Dear Bonnie,

REB #: 2013-2932
Project Title: Exploring Behaviour in Blended Environments

Effective Date: April 11, 2013
Expiry Date: April 11, 2014

The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans*. This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Sincerely,

[redacted]

Dr. Sophie Jacques, Chair

Post REB Approval: On-going Responsibilities of Researchers

After receiving ethical approval for the conduct of research involving humans, there are several ongoing responsibilities that researchers must meet to remain in compliance with University and Tri-Council policies.

1. Additional Research Ethics approval
Prior to conducting any research, researchers must ensure that all required research ethics approvals are secured (in addition to this one). This includes, but is not limited to, securing appropriate research ethics approvals from: other institutions with whom the PI is affiliated; the research institutions of research team members; the institution at which participants may be recruited or from which data may be collected; organizations or groups (e.g. school boards, Aboriginal communities, correctional services, long-term care facilities, service agencies and community groups) and from any other responsible review body or bodies at the research site

2. Reporting adverse events

Any significant adverse events experienced by research participants must be reported **in writing** to Research Ethics **within 24 hours** of their occurrence. Examples of what might be considered "significant" include: an emotional breakdown of a participant during an interview, a negative physical reaction by a participant (e.g. fainting, nausea, unexpected pain, allergic reaction), report by a participant of some sort of negative repercussion from their participation (e.g. reaction of spouse or employer) or complaint by a participant with respect to their participation. The above list is indicative but not all-inclusive. The written report must include details of the adverse event and actions taken by the researcher in response to the incident.

3. Seeking approval for protocol / consent form changes
Prior to implementing any changes to your research plan, whether to the protocol or consent form, researchers must submit them to the Research Ethics Board for review and approval. This is done by completing a Request for Ethics Approval of Amendment to an Approved Project form (available on the website) and submitting three copies of the form and any documents related to the change.

4. Submitting annual reports
Ethics approvals are valid for up to 12 months. Prior to the end of the project's approval deadline, the researcher must complete an Annual Report (available on the website) and return it to Research Ethics for review and approval before the approval end date in order to prevent a lapse of ethics approval for the research. Researchers should note that no research involving humans may be conducted in the absence of a valid ethical approval and that allowing REB approval to lapse is a violation of University policy, inconsistent with the TCPS (article 6.14) and may result in suspension of research and research funding, as required by the funding agency.

5. Submitting final reports
When the researcher is confident that no further data collection or analysis will be required, a Final Report (available on the website) must be submitted to Research Ethics. This often happens at the time when a manuscript is submitted for publication or a thesis is submitted for defence. After review and approval of the Final Report, the Research Ethics file will be closed.

6. Retaining records in a secure manner
Researchers must ensure that both during and after the research project, data is securely retained and/or disposed of in such a manner as to comply with confidentiality provisions specified in the protocol and consent forms. This may involve destruction of the data, or continued arrangements for secure storage. Casual storage of old data is not acceptable.

It is the Principal Investigator's responsibility to keep a copy of the REB approval letters. This can be important to demonstrate that research was undertaken with Board approval, which can be a requirement to publish (and is required by the Faculty of Graduate Studies if you are using this research for your thesis).

Please note that the University will securely store your REB project file for 5 years after the study closure date at which point the file records may be permanently destroyed.

7. Current contact information and university affiliation
The Principal Investigator must inform the Research Ethics office of any changes to contact information for the PI (and supervisor, if appropriate), especially the electronic mail address, for the duration of the REB approval. The PI must inform Research Ethics if there is a termination or interruption of his or her affiliation with Dalhousie University.

8. Legal Counsel
The Principal Investigator agrees to comply with all legislative and regulatory requirements that apply to the project. The Principal Investigator agrees to notify the University Legal Counsel office in the event that he or she receives a notice of non-compliance, complaint or other proceeding relating to such requirements.

9. Supervision of students
Faculty must ensure that students conducting research under their supervision are aware of their responsibilities as described above, and have adequate support to conduct their research in a safe and ethical manner.

Informed Consent

Exploring sharing information in virtual environments.

Principal Investigators: Mohammad Salimian, Faculty of Computer Science

Dr. Derek Reilly, Faculty of Computer Science

Dr. Kirstie Hawkey, Faculty of Computer Science

Dr. Bonnie MacKay, Faculty of Computer Science

Trevor Poole, Faculty of Computer Science

Juliano Franz, Faculty of Computer Science

Contact Person: Bonnie MacKay, Faculty of Computer Science, bmackay@cs.dal.ca

We invite you to take part in a research study being conducted by Bonnie MacKay at Dalhousie University. Your participation in this study is voluntary and you may withdraw from the study at any time. Your academic (or employment) performance evaluation will not be affected by whether or not you participate. To be eligible to participate in the study, you must be a Dalhousie University student. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study might not benefit you, but we might learn things that will benefit others. You should discuss any questions you have about this study with Bonnie MacKay.

The purpose of the study is to help us learn how users share documents in a virtual world environment. You will be asked to participate in an hour-long study where you will perform a set of tasks with real documents in a virtual world (e.g., deck of cards and paper documents). You and another participant will be seated at a table with a projected shared space on the table. Another person will be at a remote location where they will connect with you using a virtual world client. You can see their documents in the shared space on your table and will either communicate with the remote person using just audio or with an avatar. You will be video taped.

You will be compensated $15 for participating in the study; you can withdraw from the study at any time without consequence. A researcher is always available over the study period by email or to meet in person to answer any questions you may have or address any problems that you may experience with the tasks.

At the beginning of the study, you will meet with an investigator (in the Mona Campbell building). At this initial meeting you will be asked to give consent to do the study and to fill in a background questionnaire detailing your experience with sharing and editing documents with others. You will be given a general description of the type of tasks we want you to do during the study. After doing a set of tasks, you will fill in a questionnaire asking you about you about your opinions of the task. At the end of the study, you will participate in short interview with your partner that will ask you to share your experiences doing the tasks.

All personal and identifying data will be kept confidential. Anonymity of textual data will be preserved by using pseudonyms. All data collected in the video, questionnaires and interviews will use pseudonyms (e.g., an ID number) to ensure your confidentiality. The informed consent form and all research data will be kept in a secure location under confidentiality in accordance to University policy for 5 years post publication.

In the event that you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Catherine Connors, Director, Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance: phone: (902) 494-1462, email: Catherine.connors@dal.ca.

Demographic Questionnaire

Part I - Please fill in the following information:

1. Age: ________

2. Gender: Male Female

3. Faculty: ________________________________

Level/Year: 1st Year Undergraduate 2nd Year Undergraduate

3rd Year Undergraduate 4th Year Undergraduate

Graduate – Masters Graduate – PhD

Other ______________

4. How often do you work in groups (e.g., group work for school, for your job)?

Very Infrequently (less than twice times a year)	Infrequently (3-5 times a year)	Sometimes (6-10 times a year)	Frequently (10-20 times a year)	**Very Frequently** (more than 20 times a year)	N/A (do not do this)

5. On average, how often do you do the following activities: (please select appropriate frequency for each activity, or N/A)

	Very Infrequently (less than twice a month)	Infrequently (3-5 times a month)	Sometimes (1-3 times a week)	Frequently (4-10 times a week)	**Very Frequently** (10 times a week)	N/A (do not do this)

Share paper documents						
Share digital documents						

6. Approximately**,** what percentage of the documents that you shared over the last 6 months have contained what you to consider private or sensitive data:

	1-10%	10-25%	26-50%	51-75%	76+%	N/A (they do not contain this data)
Share paper documents						
Share digital documents						

7. How do you tend to share paper documents?
8. How do you tend to share digital documents?
9. How do you 'hide' private or sensitive data when sharing paper documents?

Post Task Questionnaires

Post Task Questionnaires - Card Game

1.	It was easy to hide the cards/ from the other person at the table.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
2.	It was easy to hide the cards from the remote person.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
3.	It was easy to share the cards with the other person at the table.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
4.	It was easy to share the cards with the remote person.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
5.	It was easy to tell if there was someone near me or near the table in the virtual world.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
6.	I trusted the remote card game I shared while playing the card games.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree

Post Task Questionnaires - Guessing Game

1.	It was easy to hide the document from the other person at the table.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
2.	It was easy to hide the document from the remote person.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
3.	It was easy to share the document with the other person at the table.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
4.	It was easy to share the document with the remote person.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
5.	It was easy to tell if there was someone near me or near the table in the virtual world.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
6.	I trusted the remote person with the information I shared while playing the card games.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree

Post Task Questionnaires – Bill Sharing

1.	It was easy to hide the topic from the other person at the table.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
2.	It was easy to hide the topic from the remote person.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
3.	It was easy to share the topic with the other person at the table.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
4.	It was easy to share the topic with the remote person.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
5.	It was easy to tell if there was someone near me or near the table in the virtual world.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
6.	I trusted the remote person with the topic I shared while playing the card games.	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree

Post-task Interview

- What visual method of the virtual world did you like using best? Why?
- Was there a visual method that you think would be better for one tasks that you did? Why?
- Which visual method do you think helped you understand that people in the virtual
- world, could see your real documents? Why? Which one was the least helpful? Why?
- For what types of tasks do you think just having the avatar would be helpful?
- For what types of tasks do you think just having the virtual map of the room helpful?
- For what types of tasks do you think having the entire café set up around you helpful?
- Did you trust that your information was 'safe' or kept private when you were in the virtual world knowing that others could possibly view your documents? Why or why not?
- Was there any view where you felt more comfortable with sharing your documents?
- How did you tend to keep your documents/cards hidden from the others?
- Did you feel it easier to keep the cards/documents hidden from the person at the table or the one remotely? Why?
- Did you feel it easier to share the cards/documents with the person at the table or the one remotely? Why?
- Do you think that a virtual world environment is a good domain for sharing and possibility editing documents? Why or why not?
- Do you have any other comments or feedback?

APPENDIX B – ETHIC DOCUMENTS FOR EXPLORING GROUP AWARENESS IN AN IMMERSIVE MIXED REALITY ENVIRONMENT

Dalhousie Ethic Board's Letter of Approval

DALHOUSIE UNIVERSITY
Research Services

Social Sciences & Humanities Research Ethics Board
Letter of Approval

July 28, 2016

Mohamad H Salimian
Computer Science\Computer Science

Dear Mohamad H,

REB #: 2016-3909
Project Title: Exploring Group (workspace) Awareness in a Mixed Reality Work Environment During a Mixed-focus Collaboration in a Small group

Effective Date:
Expiry Date: July 28, 2017

The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Sincerely,

[redacted]

Dr. Karen Beazley, Chair

Post REB Approval: On-going Responsibilities of Researchers

After receiving ethical approval for the conduct of research involving humans, there are several ongoing responsibilities that researchers must meet to remain in compliance with University and Tri-Council policies.

1. Additional Research Ethics approval
Prior to conducting any research, researchers must ensure that all required research ethics approvals are secured (in addition to this one). This includes, but is not limited to, securing appropriate research ethics approvals from: other institutions with whom the PI is affiliated; the research institutions of research team members; the institution at which participants may be recruited or from which data may be collected; organizations or groups (e.g. school boards, Aboriginal communities, correctional services, long-term care facilities, service agencies and community groups) and from any other responsible review body or bodies at the research site

2. Reporting adverse events

Any significant adverse events experienced by research participants must be reported **in writing** to Research Ethics **within 24 hours** of their occurrence. Examples of what might be considered "significant" include: an emotional breakdown of a participant during an interview, a negative physical reaction by a participant (e.g. fainting, nausea, unexpected pain, allergic reaction), report by a participant of some sort of negative repercussion from their participation (e.g. reaction of spouse or employer) or complaint by a participant with respect to their participation. The above list is indicative but not all-inclusive. The written report must include details of the adverse event and actions taken by the researcher in response to the incident.

3. Seeking approval for protocol / consent form changes
Prior to implementing any changes to your research plan, whether to the protocol or consent form, researchers must submit a description of the proposed changes to the Research Ethics Board for review and approval. This is done by completing an Amendment Request (available on the website). Please note that no reviews are conducted in August.

4. Submitting annual reports
Ethics approvals are valid for up to 12 months. Prior to the end of the project's approval deadline, the researcher must complete an Annual Report (available on the website) and return it to Research Ethics for review and approval before the approval end date in order to prevent a lapse of ethics approval for the research. Researchers should note that no research involving humans may be conducted in the absence of a valid ethical approval and that allowing REB approval to lapse is a violation of University policy, inconsistent with the TCPS (article 6.14) and may result in suspension of research and research funding, as required by the funding agency.

5. Submitting final reports
When the researcher is confident that no further data collection or participant contact will be required, a Final Report (available on the website) must be submitted to Research Ethics. After review and approval of the Final Report, the Research Ethics file will be closed.

6. Retaining records in a secure manner
Researchers must ensure that both during and after the research project, data is securely retained and/or disposed of in such a manner as to comply with confidentiality provisions specified in the protocol and consent forms. This may involve destruction of the data, or continued arrangements for secure storage. Casual storage of old data is not acceptable.

It is the Principal Investigator's responsibility to keep a copy of the REB approval letters. This can be important to demonstrate that research was undertaken with Board approval, which can be a requirement to publish (and is required by the Faculty of Graduate Studies if you are using this research for your thesis).

Please note that the University will securely store your REB project file for 5 years after the study closure date at which point the file records may be permanently destroyed.

7. Current contact information and university affiliation
The Principal Investigator must inform the Research Ethics office of any changes to contact information for the PI (and supervisor, if appropriate), especially the electronic mail address, for the duration of the REB approval. The PI must inform Research Ethics if there is a termination or interruption of his or her affiliation with Dalhousie University.

8. Legal Counsel
The Principal Investigator agrees to comply with all legislative and regulatory requirements that apply to the project. The Principal Investigator agrees to notify the University Legal Counsel office in the event that he or she receives a notice of non-compliance, complaint or other proceeding relating to such requirements.

9. Supervision of students
Faculty must ensure that students conducting research under their supervision are aware of their responsibilities as described above, and have adequate support to conduct their research in a safe and ethical manner.

Informed Consent Form

Informed Consent

Exploring sharing information in virtual environments.

Principal Investigators: Mohamad.H Salimian, Faculty of Computer Science

Dr. Derek Reilly, Faculty of Computer Science

Dr. Stephen Brooks, Faculty of Computer Science

Robert Mundle, Faculty of Computer science

Akshay Gahlon, Faculty of Computer science

Contact Person: Mohamad Salimian, Faculty of Computer Science, salimian@dal.ca

We invite you to take part in a research study being conducted by Mohamad Salimian at Dalhousie University. Your participation in this study is voluntary and you may withdraw from the study at any time without incurring any form of penalty. Your academic (or employment) performance evaluation will not be affected by whether or not you participate. To be eligible to participate in the study you should be at least 18 years old. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study might not benefit you, but we might learn things that will benefit others. You should discuss any questions you have about this study with Mohamad Salimian.

The purpose of the study is to evaluate whether an immersive environment and a virtual tabletop can help collaborators increase their group awareness, in comparison with manipulating information on a physical tabletop. You will be asked to participate in an hour and a half-long study where you will perform a set of 3D manipulation tasks on a physical tabletop or/and inside an immersive virtual environment. The brake down of the one and half hours is: 15 minutes at the beginning of the study for training, 45 minutes for finishing all of the tasks (5 minutes for each task), 15 minutes answering questionnaire and 15 minutes for the post study interview.

You may work around a physical tabletop with another collaborator or/and you will wear a Head Mount Display (HMD) to work remotely with other collaborators and through an immersive virtual environment. You will work on 3D task manipulation (e.g. assembling and dissembling a 3D model).

You will be videotaped. To ensure anonymity of all participants, all data collected (including the questionnaire data and video data) will be treated anonymously by using pseudonyms, which will be stored separately from all data. All video and electronic data (data analysis results, transcribed videos and interviews, sensors' logs, videos) will be stored on a secure server and will be accessed and processed on a secure computer (password protected) only by the researchers associated with the project. We will use video footage in our publications unless instructed against by an individuals' consent form. To ensure anonymity of all participants, we will fade out all faces before using the footage in any publication.

HMD provides an immersive virtual reality experience which can have adverse temporary motion sickness upon removing the HMD. You can remove HMD any time that you feel uncomfortable to take a break or withdraw from the study.

There are no direct benefits for you taking part in this research project. There are indirect benefits such as the opportunity to use state of the art interface technology, advance research knowledge, and potentially benefit others.

You will be compensated $20 for participating in the study; you can withdraw from the study at any time without consequence. A researcher is always available over the study period by email or to meet in person to answer any questions you may have or address any problems that you may experience with the tasks.

Prior to meeting us for the study, you be will asked to fill in a background questionnaire online detailing your experience with sharing and editing documents with others which should take about 5 minutes. For the study, you will meet with investigators in the Mona Campbell building where you will first be given a general description of the type of tasks we want you to do during the study. After doing a set of tasks, you will fill in a questionnaire asking you about you about your opinions of the task. At the end of the study, you will participate in short interview with your partner that will ask you to share your experiences doing the tasks.

All personal and identifying data will be kept confidential. Anonymity of textual data will be preserved by using pseudonyms. All data collected in the video, questionnaires and interviews will use pseudonyms (e.g., an ID number) to ensure your confidentiality. The informed consent form and all research data will be kept in a secure location under confidentiality. The informed consent form and all research data will be kept in a secure location for 5 years post publication. After this span of time, the paper materials will be shredded and the electronic will be zeroed using a low-level format operation.

In the event that you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance: phone: 902-494-3423 email: ethics@dal.ca.

Demographic Questionnaire

Part I - Please fill in the following information:

1. Age: ________

2. Gender: ☐ Male ☐ Female ☐ Other

3. Faculty if applicable: ________________________________

4. Education Level/Year:

☐ Undergraduate ☐ Graduate – Masters ☐ Graduate – PhD

☐ Other ______________

5- Have you experienced motion sickness before?

☐ Yes ☐ No

6- Have you had experience with 3D models before?

☐ 3D model software or CAD tools______________

☐ 3D printers ☐ Other ______________

7- Have you used any type of head mount display before?

☐ Oculus Rift ☐ HTC Vive ☐ Sony PlayStation VR

☐ Google Cardboard (similar)

☐ Other ______________

8- How do you rate your experience in group work and collaborations.

Very comfortable	comfortable	Neutral	Uncomfortable	Very Uncomfortable

9- How do you rate your team work and collaborations skills from 1 - 5

1 2 3 4 5

Limited skills Very Skillful

10. How often do you work in groups (e.g., group work for school, for your job)?

Very Infrequently (less than twice times a year)	Infrequently (3-5 times a year)	Sometimes (6-10 times a year)	Frequently (10-20 times a year)	Very Frequently (more than 20 times a year)	N/A (do not do this)

11. On average, how often do you do the following activities: (please select appropriate frequency for each activity, or N/A)

	Very Infrequently (less than twice a month)	Infrequently (3-5 times a month)	Sometimes (1-3 times a week)	Frequently (4-10 times a week)	Very Frequently (10 times a week)	N/A (do not do this)
Work remotely with your group						
Working on a large display (touch						

12. When you are working locally with other collaborators, approximately, what percentage of time you are aware of other co-located collaborators activities

	1-10%	10-25%	26-50%	51-75%	76+%	N/A (they do not contain this data)
Their location in the room						
Their body language						

Their actions (sharing, manipulating, editing)						

13. When you are working remotely with other collaborators, approximately, what percentage of time you are aware of co-located collaborators activities

	1-10%	10-25%	26-50%	51-75%	76+%	N/A (they do not contain this data)
Their location in the room						
Their body language						
Their actions (sharing, manipulating, editing)						

14. How frequent you felt excluded from a group activity in each case

	1-10%	10-25%	26-50%	51-75%	76+%	N/A (they do not contain this data)
Working as a remote collaborator						
Working as a co-located collaborator						

15. How often do use the following to share documents with others:

	Very Infrequently (less than twice a month)	Infrequently (3-5 times a month)	Sometimes (1-3 times a week)	Frequently (4-10 times a week)	Very Frequently (10 times a week)	N/A (do not do this)

Video conferencing						
Skype						
Google hangouts						
Google drive drop box or another cloud based system						
Use email to share						
Send by mail (external or internal mail)						
In person (exchange face to face)						
Other:						
Other:						

16. How often do use the following for working on a digital document with others

	Very Infrequently (less than twice a month)	Infrequently (3-5 times a month)	Sometimes (1-3 times a week)	Frequently (4-10 times a week)	Very Frequently (10 times a week)	N/A (do not do this)
Remote desktop/screen sharing						
Crowd around a monitor or computer						
Large screen or projection						
Using multiple devices at once (e.g., you on your phone,						

someone else on their laptop)						
Other:						
Other:						

Post Condition Questionnaires

1	How do you rate your satisfaction level about Interacting with shared 3D parts in relation to working with other collaborators?	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
		1	2	3	4	5
2	Showing the virtual hands of the remote /co-located collaborators was informative for me and helped me to be better work with them	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
3	Showing the virtual hands of the remote /co-located collaborators was informative for me and helped me to be better work with them	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
4	Showing the position of the of the remote /co-located collaborators was informative for me and helped me to be better work with them	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
5	Showing the position of the of the remote /co-located collaborators was informative for me and helped me to be better work with them	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
6	There was a time that I felt excluded by the remote collaborator.	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
7	There was a time that I felt excluded by the remote collaborator.	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5

8	There was a time that I felt excluded by the other co-located collaborator.	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
9	Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to establish a stronger mutual understanding with the remote participant Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my communication with the remote/co-located participant	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
10	Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants while we were working on Assembly task Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants while I was looking to find the buttons on different sides of the 3D models	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
11	Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants during the Illustration task. Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to establish a stronger mutual understanding with the remote participant	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5
12	Hover/Fishtank/Tabletop condition in comparison to	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree

	other conditions helped me to improve my communication with the remote/co-located participant Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants while we were working on Assembly task	1	2	3	4	5
13	Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants while I was looking to find the buttons on different sides of the 3D models	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5

APPENDIX C – ETHIC DOCUMENTS FOR IMRCE TOOLKIT

Dalhousie Ethic Board's Letter of Approval

DALHOUSIE UNIVERSITY
Research Services

Social Sciences & Humanities Research Ethics Board
Letter of Approval

February 13, 2018

Mohamad H. Salimian
Computer Science\Computer Science

Dear Mohamad H.,

REB #: 2017-4316
Project Title: Evaluating the use of a Unity toolkit for prototyping an immersive mixed reality collaborative environment

Effective Date: February 13, 2018
Expiry Date: February 13, 2019

The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Sincerely,

[redacted]

Dr. Karen Beazley, Chair

Post REB Approval: On-going Responsibilities of Researchers

After receiving ethical approval for the conduct of research involving humans, there are several ongoing responsibilities that researchers must meet to remain in compliance with University and Tri-Council policies.

1. Additional Research Ethics approval
Prior to conducting any research, researchers must ensure that all required research ethics approvals are secured (in addition to this one). This includes, but is not limited to, securing appropriate research ethics approvals from: other institutions with whom the PI is affiliated; the research institutions of research team members; the institution at which participants may be recruited or from which data may be collected; organizations or groups (e.g. school boards, Aboriginal communities, correctional services, long-term care facilities, service agencies and community groups) and from any other responsible review body or bodies at the research site

2. Reporting adverse events

Any significant adverse events experienced by research participants must be reported **in writing** to Research Ethics **within 24 hours** of their occurrence. Examples of what might be considered "significant" include: an emotional breakdown of a participant during an interview, a negative physical reaction by a participant (e.g. fainting, nausea, unexpected pain, allergic reaction), report by a participant of some sort of negative repercussion from their participation (e.g. reaction of spouse or employer) or complaint by a participant with respect to their participation. The above list is indicative but not all-inclusive. The written report must include details of the adverse event and actions taken by the researcher in response to the incident.

3. Seeking approval for protocol / consent form changes
Prior to implementing any changes to your research plan, whether to the protocol or consent form, researchers must submit a description of the proposed changes to the Research Ethics Board for review and approval. This is done by completing an Amendment Request (available on the website). Please note that no reviews are conducted in August.

4. Submitting annual reports
Ethics approvals are valid for up to 12 months. Prior to the end of the project's approval deadline, the researcher must complete an Annual Report (available on the website) and return it to Research Ethics for review and approval before the approval end date in order to prevent a lapse of ethics approval for the research. Researchers should note that no research involving humans may be conducted in the absence of a valid ethical approval and that allowing REB approval to lapse is a violation of University policy, inconsistent with the TCPS (article 6.14) and may result in suspension of research and research funding, as required by the funding agency.

5. Submitting final reports
When the researcher is confident that no further data collection or participant contact will be required, a Final Report (available on the website) must be submitted to Research Ethics. After review and approval of the Final Report, the Research Ethics file will be closed.

6. Retaining records in a secure manner
Researchers must ensure that both during and after the research project, data is securely retained and/or disposed of in such a manner as to comply with confidentiality provisions specified in the protocol and consent forms. This may involve destruction of the data, or continued arrangements for secure storage. Casual storage of old data is not acceptable.

It is the Principal Investigator's responsibility to keep a copy of the REB approval letters. This can be important to demonstrate that research was undertaken with Board approval, which can be a requirement to publish.

Please note that the University will securely store your REB project file for 5 years after the study closure date at which point the file records may be permanently destroyed.

7. Current contact information and university affiliation
The Principal Investigator must inform the Research Ethics office of any changes to contact information for the PI (and supervisor, if appropriate), especially the electronic mail address, for the duration of the REB approval. The PI must inform Research Ethics if there is a termination or interruption of his or her affiliation with Dalhousie University.

8. Legal Counsel
The Principal Investigator agrees to comply with all legislative and regulatory requirements that apply to the project. The Principal Investigator agrees to notify the University Legal Counsel office in the event that he or she receives a notice of non-compliance, complaint or other proceeding relating to such requirements.

9. Supervision of students
Faculty must ensure that students conducting research under their supervision are aware of their responsibilities as described above, and have adequate support to conduct their research in a safe and ethical manner.

Informed Consents Form

Informed Consent

Exploring sharing information in virtual environments.

Principal Investigators: Mohamad.H Salimian, Faculty of Computer Science

Dr. Derek Reilly, Faculty of Computer Science

Dr. Stephen Brooks, Faculty of Computer Science

Contact Person: Mohamad Salimian, Faculty of Computer Science, salimian@dal.ca

We invite you to take part in a research study being conducted by Mohamad Salimian at Dalhousie University. Your participation in this study is voluntary and you may withdraw from the study at any time without incurring any form of penalty. Your academic (or employment) performance evaluation will not be affected by whether you participate. To be eligible to participate in the study you should be at least 18 years old, with experience in software programming and developing. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study might not benefit you, but we might learn things that will benefit others. You should discuss any questions you have about this study with Mohamad Salimian.

The purpose of the study is to evaluate whether using IMRCE toolkit help researcher and software developer for rapid prototyping an immersive mixed reality collaborative environment.

You will be asked to participate in an hour and half long study where you will be asked to use the IMRCE toolkit to develop three simple software developing scenarios for collaboration between remote and co-located collaborators. The brake down of the ten hours is:

First day: 30 minutes training for using the toolkit, 3.5 hours to finish the given programming task. Six minutes to fill out the post-task questionnaire (in total 30 minutes for five tasks), 15 minutes answering post-condition questionnaire and 15 minutes for the post-condition interview.

Second day: 30 minutes training for working with the Unity software, 3.5 hours to finish the given programming tasks. Six minutes to fill out the post-task questionnaire (in total 30 minutes for five tasks), 5 minutes answering post-condition questionnaire and 25 minutes for the post-condition interview and post-experiment interview.

To ensure anonymity of all participants, all data collected (including the questionnaire data) will be treated anonymously by using pseudonyms, which will be stored separately from all data. All electronic data (data analysis results, transcribed audio from interviews, sensors' logs,) will be stored on a secure server and will be accessed and processed on a secure computer (password protected) only by the researchers associated with the project.

Head Mount Display provides an immersive virtual reality experience which can have adverse temporary motion sickness, strain and disorientation upon removing the HMD. You are not required to wear the HMD and you can remove HMD any time that you feel uncomfortable to take a break or withdraw from the study. You can wear the HMD to test the results otherwise one of our researchers will wear the HMD to check the results.

There are no direct benefits for you taking part in this research project. There are indirect benefits such as the opportunity to use state of the art interface technology, advance research knowledge, and potentially benefit others.

You will be compensated $20 for participating in the study; you can withdraw from the study at any time without consequence before completing the study. You cannot withdraw from the study after the study is completed. A researcher is always available over the study period by email or to meet in person to answer any questions you may have or address any problems that you may experience with the tasks.

Prior to meeting us for the study, you be will asked to fill in a background and screening questionnaire online detailing your experience with developing software which should take about 5 minutes. For the study, you will meet with investigators in the Mona Campbell building where you will first be given a general description of the task we want you to do during the study. We use the first 30 minutes to show you how to use the toolkit. You will complete the task in five steps. You will fill in a questionnaire after each step, asking you about your feedback. At the end of the study, you will participate in short interview that will ask you to share your experiences doing the task. We audio record the interview.

All personal and identifying data will be kept confidential. Anonymity of textual data will be preserved by using pseudonyms. All data collected in questionnaires and interviews will use pseudonyms (e.g., an ID number) to ensure your confidentiality. The informed consent form and all research data will be kept in a secure location under confidentiality. The informed consent form and all research data will be kept in a secure location for 5 years post publication. After this span of time, the paper materials will be shredded and the electronic will be zeroed using a low-level format operation.

In the event that you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance: phone: 902-494-3423 email: ethics@dal.ca.

Demographic and Screening Questionnaire

Part I - Please fill in the following information:

1. Age: ________

2. Gender: ☐ Male ☐ Female ☐ Other

3. Faculty if applicable: ________________________________

4. Education Level/Year:

☐ Undergraduate ☐ Graduate – Masters ☐ Graduate – PhD

☐ Other ______________

5- Have you developed and Unity software before?

☐ Yes ☐ No

6- Have you had experience with 3D models before?

☐ 3D model software or CAD tools______________

☐ 3D printers ☐ Other ______________

7- Have you used any type of head mount display before?

☐ Oculus Rift ☐ HTC Vive ☐ Sony PlayStation VR

☐ Google Cardboard (similar)

☐ Other ______________

8- How do you rate your experience in developing Unity applications.

No experience Beginner Professional Advanced

Post-Condition Questionnaires

Post-Condition Questionnaires after IRMCE condition

Please respond to the following statements using the given scale (circle response):

Specific Feature Questions						
1.	Using the IMRCE toolkit to add touch gestures to 3D objects.	1	2	3	4	5
		Very easy	Somewhat easy	Neutral	Somewhat hard	Very hard
2.	Using the IMRCE toolkit to set up the unity server/client	1	2	3	4	5
		Very easy	Somewhat easy	Neutral	Somewhat hard	Very hard
3.	Using the IMRCE toolkit to add interactivity to 3D objects for VR environment	1	2	3	4	5
		Very easy	Somewhat easy	Neutral	Somewhat hard	Very hard
4.	Using the IMRCE toolkit to add virtual hands	1	2	3	4	5
		Very easy	Somewhat easy	Neutral	Somewhat hard	Very hard
5.	Using the IMRCE toolkit to add position tracking	1	2	3	4	5
		Very easy	Somewhat easy	Neutral	Somewhat hard	Very hard
6.	The IMRCE toolkit was helpful to add touch gestures to 3D objects	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
7.	The IMRCE toolkit was helpful to add interactivity to 3D objects for VR environment	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
8.	The IMRCE toolkit was helpful to set up the unity server/client	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
9.		1	2	3	4	5

	The IMRCE toolkit was helpful to add virtual hands	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
10.	The IMRCE toolkit was helpful to add position tracking to the application	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
11.	I prefer to look for alternative solutions to add VR interactivity to 3D objects for virtual environment	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
12.	I prefer to look for alternative solutions to add virtual hands	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
13.	I prefer to look for alternative solutions to add position tracking to the application	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
14.	I prefer to look for alternative solutions to add touch gestures to 3D objects	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
15.	I prefer to look for alternative solutions to set up the unity server/client	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree

Post-Condition Questionnaires after No-IRMCE condition

Specific Feature Questions						
1.	Using the external toolkits/libraries/scripting to add touch gestures to 3D objects.	1 Very easy	2 Somewhat easy	3 Neutral	4 Somewhat hard	5 Very hard
2.	Using the toolkits/libraries/scripting to set up the unity server/client	1 Very easy	2 Somewhat easy	3 Neutral	4 Somewhat hard	5 Very hard
3.	Using the toolkits/libraries/scripting to add interactivity to 3D objects for VR environment	1 Very easy	2 Somewhat easy	3 Neutral	4 Somewhat hard	5 Very hard
4.	Using toolkits/libraries/scripting to add virtual hands	1 Very easy	2 Somewhat easy	3 Neutral	4 Somewhat hard	5 Very hard
5.	Using toolkits/libraries/scripting to add position tracking	1 Very easy	2 Somewhat easy	3 Neutral	4 Somewhat hard	5 Very hard
6.	External Toolkits/libraries/scripting were helpful to add touch gestures to 3D objects	1 Strongly Disagree	2 Somewhat Disagree	3 Neutral	4 Somewhat Agree	5 Strongly Agree
7.		1	2	3	4	5

	External Toolkits/libraries/scripting were helpful to add interactivity to 3D objects for VR environment	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
8.	External Toolkits/libraries/scripting were helpful to set up the unity server/client	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
9.	External Toolkits/libraries/scripting were was helpful to add virtual hands	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
10.	External Toolkits/libraries/scripting were helpful to add position tracking to the application	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
11.	I prefer to look for alternative solutions to add VR interactivity to 3D objects for virtual environment	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
12.	I prefer to look for alternative solutions to add virtual hands	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
		1	2	3	4	5

13.	I prefer to look for alternative solutions to add position tracking to the application	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
14.	I prefer to look for alternative solutions to add touch gestures to 3D objects	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
15.	I prefer to look for alternative solutions to set up the unity server/client	1	2	3	4	5
		Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree

Post-condition Interview (semi structured)

1. How did you like the to the IMRCE toolkit?
2. Did you find the IMRCE toolkit useful to develop applications?
3. What features of the application were more helpful? Why?
4. What were the problems you had in using the applications?
5. Do you think using the toolkit helped you to save time to having rapid prototyping?
6. For what types of tasks do you think our system is helpful?
7. Do you have any other comments or feedback?

APPENDIX D – RESULTS OF SATASTICAL TEST FOR PSOT TASK QUESTIONNAIRES

Table 11: The results of postcondition questionnaires for using position tracking

Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
1	2	3	4	5

Q1) Showing the position of the of the remote /co-located collaborators was informative for me and helped me to be better work with them

Q2) Showing the position of the remote /co-located collaborators increased my awareness related to them and their actions.

Question	Location	P_{value}	χ^2	Condition	Mean	SD
Q1 - Helping	Remote	0.09	4.813	Hover	3.98	1.090
				Fishtank	4.13	1047
				Tabletop	3.69	1.130
	Collocated	**10^{-7}**	**15.904**	**Hover**	**4.11**	**0.984**
				Fishtank	**4.28**	**0.856**
				Tabletop	**3.56**	**1.192**
Q2 - Awareness	Remote	0.062	5.559	Hover	4.19	1.029
				Fishtank	4.148	1.035
				Tabletop	3.83	1.193
	Collocated	**0.038**	**6.552**	**Hover**	**4.26**	**1.049**
				Fishtank	**4.259**	**1.0128**
				Tabletop	3.833	1.240
Combined	**Remote**	**0.019**	**7.903**	**Hover**	**4.083**	**0.960**
				Fishtank	**4.138**	**0.997**
				Tabletop	**3.759**	**1.053**
	Collocated	**0.001**	**14.235**	**Hover**	**4.185**	**0.891**
				Fishtank	**4.268**	**0.878**
				Tabletop	**3.694**	**1.039**

Table 12: The results of postcondition questionnaires for using hand Embodiments.

Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree		
1	2	3	4	5		
Q1) Showing the virtual hands of the remote /co-located collaborators were informative for me and helped me to be better work with them						
Question	Location	P_{value}	χ^2	Condition	Mean	SD
Q1 - Hands	Remote	0.235	2.893	Hover	4.22	0.965
				Fishtank	4.2	0.939
				Tabletop	3.93	1.130
	Collocated	0.070	5.328	Hover	4.33	0.847
				Fishtank	4.39	0.763
				Tabletop	3.98	1.09

Table 13: Pairwise comparison for significant results.

Location	Pair comparison	P_{value}	Condition	95% conf.	
				Lover Bond	Upper Bond
Q1 - Collocated	Hover - Fishtank	0.316	Hover	-.497	0.163
	Hover- Tabletop	**0.006**	**Fishtank**	**0.167**	**0.944**
	Tabletop - Fishtank	**0.001**	**Tabletop**	**0.331**	**1.113**
Combined-Collocated	Hover - Fishtank	0.605	Hover	0.404	0.238
	Hover- Tabletop	**0.006**	**Fishtank**	**0.147**	**0.835**
	Tabletop - Fishtank	**0.002**	**Tabletop**	**0.230**	**0.918**

Table 14: The results of postcondition questionnaires for communication and coordination.

Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
1	2	3	4	5

Q1) Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to establish a stronger mutual understanding with the remote participant

Q2) Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my communication with the remote/co-located participant

Q3) Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants while I was while I was working on the Assembly task

Q4) Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants while I was looking to find the buttons on different sides of the 3D models

Q5) Hover/Fishtank/Tabletop condition in comparison to other conditions helped me to improve my collaboration with other participants during the Illustration task.

Question	Location	P_{value}	χ^2	Condition	Mean	SD
Q1 - mutual understanding	Remote	0.451	1.592	Hover	4.06	1.056
				Fishtank	3.72	1.32
				Tabletop	4.11	0.832
	Collocated	0.819	0.4	Hover	4.33	0.686
				Fishtank	4.56	0.705
				Tabletop	4.39	0.778
Q2 - communication	Remote	0.315	2.311	Hover	4.28	0.752
				Fishtank	3.94	0.998
				Tabletop	3.83	0.924
	Collocated	0.673	0.792	Hover	3.72	0.752
				Fishtank	3.89	0.963
				Tabletop	3.72	0.575
Q3 - Assembly	**Remote**	**0.014**	**8.481**	**Hover**	**3.00**	**0970**
				Fishtank	**3.78**	**1.114**
				Tabletop	**3.72**	**0.895**
	Collocated	0.689	0.745	Hover	3.72	0.958
				Fishtank	3.94	0.938
				Tabletop	3.83	0.786
	Remote	0.516	1.321	Hover	4.06	0.802

Q4 - Searching				Fishtank	3.61	1.145
				Tabletop	4.00	0.907
	Collocated	0.578	1.098	Hover	4.33	0.84
				Fishtank	4.11	1.023
				Tabletop	4.5	0.857
Q5 - Illustration	Remote	0.436	1.661	Hover	3.44	0.922
				Fishtank	3.72	1.227
				Tabletop	3.94	0.725
	Collocated	0.28	2.542	Hover	3.56	1.199
				Fishtank	3.78	1.114
				Tabletop	4.11	0.758

Table 15: The results of postcondition questionnaires for the feeling of exclusion and attention..

Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
1	2	3	4	5

Q1) There was a time that I felt excluded by the counterpart collaborator

Q2) There was a time that I paid less attention to the remote/collocated collaborator due to their physical absence.

Question	Location	P_{value}	F (2, 106)	Condition	Mean	SD
Q1 - excluded	Remote	0.357	1.041	Hover	4.19	1.134
				Fishtank	4.28	0.856
				Tabletop	4.04	1.115
	Collocated	**0.013**	**4.513**	**Hover**	**4.37**	**1.087**
				Fishtank	**4.2**	**1.053**
				Tabletop	**3.83**	**1.225**
Q2 - Attention	Remote	0.886	0.121	Hover	3.80	1.365
				Fishtank	3.83	1.285
				Tabletop	3.72	1.265
	Collocated	**0.034**	**3.666**	**Hover**	**3.87**	**1.150**
				Fishtank	**4**	**1.133**
				Tabletop	**3.43**	**1.354**

Table 16: Pairwise comparison for significant results.

Location	Pair comparison	P_{value}	Condition	95% conf.	
				Lover Bond	Upper Bond
Q1-Excluded	Hover - Fishtank	0.303	Hover	0.155	0.488
	Hover- Tabletop	**0.006**	**Fishtank**	**0.163**	**0.911**
	Tabletop - Fishtank	0.07	Tabletop	0.488	0.155
Q2-Attention	Hover - Fishtank	0.482	Hover	0497	0.238
	Hover- Tabletop	**0.05**	**Fishtank**	**0.004**	**0.893**
	Tabletop - Fishtank	**0.028**	**Tabletop**	**0.064**	**1.084**

Table 17: The results of postcondition questionnaires for interacting with 3D objects

Very Dissatisfied	Dissatisfied	Neutral	satisfied	Very satisfied
1	2	3	4	5

Q1) How do you rate your satisfaction level about Interacting with shared 3D parts in relation to working with other collaborators?

Question	Location	P_{value}	χ^2	Condition	Mean	SD
Q1 - Interaction with 3D object	**Remote**	**0.001**	**13.629**	**Hover**	**3.7**	**1.075**
				Fishtank	**3.11**	**1.208**
				Tabletop	**2.98**	**1.107**
	Collocated	0.4	1.834	Hover	**3.74**	0.955
				Fishtank	**3.63**	1.138
				Tabletop	**3.63**	0.853

APPENDIX E – COUNTERBALANCING FOR THE SECOND STUDY

Table 18: Counterbalancing the order of performing tasks and conditions.

G1	Hover	Fishtank	Tabletop
	T1_Plane	T1_Chopper	T1_Car
	T2_Race	T2_Desert	T2_Garden
	T3_Steam	T3_Turbine	T3_Engine

G2	Fishtank	Tabletop	Hover
	T1_Chopper	T1_Car	T1_Plane
	T2_Desert	T2_Garden	T2_Race
	T3_Turbine	T3_Engine	T3_Steam

G3	Tabletop	Hover	Fishtank
	T1_Car	T1_Plane	T1_Chopper
	T2_Garden	T2_Race	T2_Desert
	T3_Engine	T3_Steam	T3_Turbine

G4	Hover	Fishtank	Tabletop
	T2_Desert	T2_Garden	T2_Race
	T3_Engine	T3_Steam	T3_Turbine
	T1_Chopper	T1_Car	T1_Plane

G5	Fishtank	Tabletop	Hover
	T2_Garden	T2_Race	T2_Desert
	T3_Steam	T3_Turbine	T3_Engine
	T1_Car	T1_Plane	T1_Chopper

G6	Tabletop	Hover	Fishtank
	T2_Race	T2_Desert	T2_Garden
	T3_Turbine	T3_Engine	T3_Steam
	T1_Plane	T1_Chopper	T1_Car

G7	Hover	Fishtank	Tabletop
	T3_Turbine	T3_Engine	T3_Steam
	T1_Car	T1_Plane	T1_Chopper
	T2_Garden	T2_Race	T2_Desert

G8	Fishtank	Tabletop	Hover
	T3_Engine	T3_Steam	T3_Turbine
	T1_Plane	T1_Chopper	T1_Car
	T2_Race	T2_Desert	T2_Garden

G9	Tabletop	Hover	Fishtank
	T3_Steam	T3_Turbine	T3_Engine
	T1_Chopper	T1_Car	T1_Plane
	T2_Desert	T2_Garden	T2_Race

G10	Hover	Fishtank	Tabletop
	T1_Car	T1_Plane	T1_Chopper
	T2_Garden	T2_Race	T2_Desert
	T3_Engine	T3_Steam	T3_Turbine

G11	Fishtank	Tabletop	Hover
	T1_Plane	T1_Chopper	T1_Car
	T2_Race	T2_Desert	T2_Garden

G12	Tabletop	Hover	Fishtank
	T1_Chopper	T1_Car	T1_Plane
	T2_Desert	T2_Garden	T2_Race

	T3_Steam	T3_Turbine	T3_Engine
G13	Hover	Fishtank	Tabletop
	T3_Steam	T3_Turbine	T3_Engine
	T1_Chopper	T1_Car	T1_Plane
	T2_Desert	T2_Garden	T2_Race
G15	Tabletop	Hover	Fishtank
	T3_Engine	T3_Steam	T3_Turbine
	T1_Plane	T1_Chopper	T1_Car
	T2_Race	T2_Desert	T2_Garden
G17	Fishtank	Tabletop	Hover
	T2_Desert	T2_Garden	T2_Race
	T3_Engine	T3_Steam	T3_Turbine
	T1_Chopper	T1_Car	T1_Plane

	T3_Turbine	T3_Engine	T3_Steam
G14	Fishtank	Tabletop	Hover
	T3_Turbine	T3_Engine	T3_Steam
	T1_Car	T1_Plane	T1_Chopper
	T2_Garden	T2_Race	T2_Desert
G16	Hover	Fishtank	Tabletop
	T2_Race	T2_Desert	T2_Garden
	T3_Turbine	T3_Engine	T3_Steam
	T1_Plane	T1_Chopper	T1_Car
G18	Tabletop	Hover	Fishtank
	T2_Garden	T2_Race	T2_Desert
	T3_Steam	T3_Turbine	T3_Engine
	T1_Car	T1_Plane	T1_Chopper

APPENDIX F - NOTICES OF PERMISSION TO USE EXCERPTS FROM AUTHOR'S PUBLICATIONS

In this Thesis, large and small excerpts were taken verbatim from two of the author's own published papers [197] [198]. Also, there are parts from another paper which is under review at the time of writing this thesis. A form of the student's contribution to the manuscript was signed and submitted to the graduate studies office. The Association of Computing Machinery (ACM) states in the ACM Author Rights linked below that the use of the author's work in their own dissertation is allowed[3].

[3] https://authors.acm.org/main.html