Hybrid Collaborative Virtual Environments

by

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Computer Science
in the Graduate College of the
University of Illinois at Chicago, 2021

Chicago, Illinois

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In memory of my grandmother, Lalithamma.

ACKNOWLEDGMENT

I would like to thank my advisor Andrew Johnson, for helping me take on this monumental journey and guiding me through every step of it. I cannot think of a better mentor. I would also like to thank my committee members Liz Marai, Debaleena Chattopadhyay, Steve Jones, Jason Leigh, and Tommy Marrinan for their guidance and valuable input throughout the process of building my thesis. Finally I would like to thank my friends Pramitha and Ashwin for all their support and my family for their patience.

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LIST OF ABBREVIATIONS

CVE	Collaborative virtual environments
HMD	Head Mounted Display
HMPD	Head Mounted Projective Displays
IIM	Individual Interaction Mode
IVR	Immersive Virtual Reality
SAGE2	Scalable Amplified Group Environment
SIM	Shared Interaction Mode

SUMMARY

Collaborative Virtual Environments have been increasingly used in supporting group work. Several collaborative systems have come up in recent years as a way of meeting the ever changing needs of group work, with asymmetric setups being the latest addition to a diverse collection of systems. In recent years, we see attempts at multi-domain collaboration. Research on interdisciplinary collaboration reveals a need for supporting a hybrid of tools and representations that are familiar to users of different domains.

In this dissertation, I present a prototype implementation of a Hybrid Collaborative Virtual Environment that combines multiple representations to facilitate multi-domain collaboration. Preliminary evaluation of the prototype showed that hybridization of different representations can lead to role formation due to dependency on representations, when users are limited to interacting with a single representation. Integrating shared views and shared interaction into this Hybrid Collaborative Virtual Environment with the help of a large shared display environment can help solve the representational dependency issue. Shared views and shared interactions enable users to freely interact with any of the different representations and also eases communication amongst them. I evaluate this integration by means of a formal study having a within group design: A group of three participants perform collaborative tasks using the Hybrid Collaborative Virtual Environment with and without the integration of shared views and shared interactions. I discuss the results of the study and show how shared views and shared interaction improves the collaborative experience.

CHAPTER 1

INTRODUCTION

Collaborative systems come in many different flavors. From facilitating a group of people to create and asynchronously edit a textual document to enabling a distributed team of users to sculpt a complex 3D model synchronously and in real time, collaborative tools have a wide spectrum owing mostly to the varied nature of tasks they are built to support. Collaborative virtual environments (CVE) are a subset of collaborative tools that have emerged as a result of the intersection of collaborative tools and virtual environments.

Collaborative systems have seen a continuous evolution starting from the early 90s, when the first collaborative systems were developed, to the state of the art. This evolution begins with collaboration transparent systems (Abdel-Wahab and Feit, 1991) (Garnkel et al., 1994) (Sun, 1991) (Microsoft, 1996) that enable shared access of legacy single user systems by multiple users in real time. We then see collaboration aware systems (Hagsand, 1996) (Barrus et al., 1996) (Greenhalgh, 1999) that incorporate group awareness into the design of the systems. This is followed by systems with subjective views (Smith and Mariani, 1997) (Leigh and Johnson, 1996) (Zhang and Furnas, 2005) (Thanyadit et al., 2018) that present different perspectives or different layers of information to different users to accommodate heterogeneity in roles and tasks among group members (Benford et al., 2001). At the same time, the CVEs have also been getting better in supporting collaboration, thanks to research efforts that have been made to improve different aspects of CVEs such as immersive experience (Musse et al., 1998), scalability

(Benford et al., 1997), response time (Macedomia et al., 1995) (Greenhalgh et al., 1999) and so on. As a next step in this progression we see asymmetric collaborative systems (Seon-Min Rhee et al., 2003) (Sugiura et al., 2018) (Asutay et al., 2005) (Hong Hua et al., 2003) (Lee et al., 2020) that enable users to collaborate not just with different perspectives but also using a heterogeneous set of hardware devices. It can be seen as a reflection of the evolving nature of group work. Of late, we also see attempts of interdisciplinary collaboration (Tsoupikova et al., 2009) (Marai et al., 2016) (Altizer et al., 2017) where experts of different disciplines come together to work on complex problems. Interdisciplinary collaboration requires the expertise of different domains in order to create a unified solution to the problem at hand.

My research interest is to explore the challenges that are present in supporting interdisciplinary collaboration through CVEs. Looking at different examples that fall under interdisciplinary collaboration, I chose the problem of architecture design as the basis for creating a prototype to explore the research opportunities. The rationale behind this choice is that apart from being a interdisciplinary (engineer, interior designer, and of late even consumers are getting involved in the design process) collaborative task, architecture design problem is a good candidate for a level 2 CVE, according to the classification framework given by (Margery et al., 1999):

> “We define collaboration (cooperation level 1) as the basic cooperation level. This is done by enabling users to perceive each other in the virtual world thanks to avatars (the 3D representation of an user) and providing ways of communicating between these users. When each user can change the scene individually, the system is said

> to support level 2 cooperation. The main limit to cooperation level 2 is that users cannot cooperate on the objects present in the scene. For example, if two users want to move the same object, a lock mechanism would ensure that only one user can perform this action. Cooperation level 3 enables such cooperation on an object."

In other words, tasks involved in architecture design require users to actively manipulate objects within the scene, yet almost never require users manipulating the same object at the same time (level 3). I wanted to focus my research more on the user aspects of CVEs, hence it was a deliberate choice to avoid problems that require efforts on issues such as conflict resolution which tend to be more on the system side of CVEs.

I created the prototype for architecture design as a hybrid of three different representations through three different applications, namely a 2D application, a 3D application, and an immersive virtual reality (VR) application, providing different perspectives as well as different representations of the shared virtual space. A key insight into interdisciplinary collaboration: "People in the same discipline will share tools that others do not use" (Cummings and Kiesler, 2008) was the guiding factor for such a hybridization of representations. It is a distributed collaborative environment. The 2D application presents a monochromatic top view of the scene over a grid layout, mimicking a floor plan, a representation that is more familiar to engineers. The VR application presents a fully immersive 360 degree view of the virtual space in 1:1 scale through a Head Mounted Display (HMD) to the user interacting with it. This could be more preferable for tasks that require precise understanding of the 3D space that is being designed. The 3D application presents an in-person perspective of the scene with a limited field of view, giving the users a driver-seat view of the scene. I created the 2D and 3D applications as custom applications on top of Scalable Amplified Group Environment (SAGE2) (Marrinan et al., 2014) leveraging the affordances of SAGE2 for collocated collaboration. This allows more than one person to simultaneously interact with, and control, both of these applications. I created the VR application using Unity 3D game engine. I chose a basic set of elements like Walls, Doors, Windows, and Furniture to provide enough interaction possibilities for evaluating the prototype and gaining insights into potential research questions. People from multiple domains come with a background of their own set of tools, representations, ways of interpreting a piece of information and so on. When such people collaborate, the nature of collaboration is more of a partnership (Cummings and Kiesler, 2008) than complementary. Keeping in line with this observation, I equipped all the three applications with all the functionalities for full interaction with the shared space using any of them.

I conducted a group user study of the prototype to gauge the usability of the prototype and to explore the research opportunities in CVEs built for supporting interdisciplinary collaboration. In the study, a group of four users were given an open ended task of designing an office space with a broad set of requirements. Chapter 4 presents methodology and results of the user study in detail. One of the key observations that I made throughout study that is also reflected in the results is that during the collaborative session the users counterbalanced what they perceived as limitations of one representation with the affordances of another representation. This led to certain tasks being almost exclusively carried out through particular applications. As each user was limited to interacting with exactly one of the three applications, this resulted in the formation of spontaneous roles (Strijbos et al., 2005) during the collaboration.

A role is any function or set of related functions assumed by people in a social interaction. The function or the set of functions may assume a wide range of forms from a simple physical action to a more detailed and complex activity. Wall creator, one responsible for alignment of furniture, layout designer, task planner, task coordinator, leader, and so on are some of the examples of roles that emerge during the collaborative sessions when people interact with the hybrid collaborative environment. The participants assume these roles either implicitly or after discussing it with the rest of the group and coming to a consensus.

While the design of the prototype is intended to support different functional roles (Strijbos et al., 2005) that are based on different domains, any spontaneous roles that form during the collaborative session should be due to the need of the collaborative work and not as an artifact of representation dependency.

Research on large displays indicate that they are effective in aiding multitasking (Czerwinski et al., 2006). We also see large displays being preferred to carry out multi-application tasks (Bi and Balakrishnan, 2009). Further, (Bakdash et al., 2006) found that large displays are better compared to smaller displays for gaining spatial knowledge of a virtual environment. In light of this, I believe that they can be effectively employed in the collaborative setup to integrate shared views and shared interactions into the collaborative setup to address the representation dependency issue. Further, providing such a shared interaction space would enable the users to interact and communicate in new ways. This led to the following research questions:

1. **How will the integration of shared views and shared interactions with the hybrid CVE affect group collaboration in such a hybrid CVE? Specifically, how will the integration affect the formation of spontaneous roles that are influenced by dependency on representations in such a hybrid CVE?**
2. **Will the integration improve the transparency of the collaborative environment?**
3. **Will the integration make it easier for the group members to communicate with each other?**
4. **Will the integration improve the work share between the group members?**

I conducted a formal user study to seek answers to these research questions. The results of the study suggest that the integration of shared views and shared interactions into the hybrid CVE does mitigate the role formation due to representation dependency and improves the transparency of the system, improves the communication between the group members, and improves the work share between them.

The rest of this dissertation is organized as follows: In Chapter 2, I present the details of a survey I conducted on the state of the art. In Chapter 3, I present the architecture and implementation of the hybrid CVE prototype that I have created. In Chapter 4, I present the details of the preliminary user study that I conducted along with the results of the study. In Chapter 5, I explain the integrated setup and the formal user study that I conducted to evaluate it, including the results of the study. In Chapter 6, I present the conclusion of this dissertation along with future research directions.

CHAPTER 2

PRIOR WORK

[*Portions of this chapter were previously published as part of (Bharadwaj and Johnson, 2020)*]

As this research involves a hybridization of different applications (representations) running on different hardware devices, in this Chapter, I present some of the existing CVEs categorized based on uniformity of hardware and software (views and representations) to enable easy comparison with the prototype I have created.

2.1 Uniform hardware with uniform views

TeamRooms (Roseman and Greenberg, 1996) is a collaborative environment based on the metaphor of shared virtual rooms. TeamRooms supports geographically distributed groups of people who need to work closely together. The system uses the metaphor of rooms that are user-defined, where each room is equipped with a shared whiteboard, chat tool and customisable groupware applets. (Mansfield et al., 1997) presents the Orbit system which is a prototype implementation of the concept of workaday activities for distributed workgroups. It is a distributed, computer supported work environment, built on the concept of locales which is a conceptual "place" for a group of people to assemble to participate in shared work. The locale aims to provide a 'ubiquitous collaborative desktop' through which users can perform both shared and individual tasks. (Li et al., 2001) present a distributed system that allows multiple people to collaboratively sculpt a 3D model. The system provides the same view of the 3D model being sculpted to all users on a standard desktop setting. (Calabrese et al., 2016) present a similar sculpting system, however they focus more on conflict resolution techniques. MeshHisto (Salvati et al., 2015) is a collaborative polygonal modelling tool that allows remote users to create low-polygonal and subdivision mesh models. The interface for MeshHisto has been developed for standard desktop workstations.

(Hsu et al., 2020) discuss a CVE that enables multiple users to interactively design and discuss architectural designs using HMDs. This collaborative system has been built using Unity3D on top of existing software for creating architectural designs. It presents every user with the same view/representation using HMDs. An asynchronous collaboration setup presented by (Chow et al., 2019) uses multi-modal recording of the participants including motion capture, audio, and video recording to convey task intentions and requests to different users of the system who then "view" these recordings and edit the scene based on the inputs from the recordings and in turn record their own inputs for other users. The same hardware and software setup is used by different users over time.

The earlier systems like TeamRooms and Orbit provide a shared virtual space where different members of the group can exchange information and communicate with each other and engage in activities like online meetings while the more recent systems tend to support more cooperation centered activities such as sculpting a 3D model and architecture design. The common criteria between all these examples is that the groups consist of members who all have the same functionalities within the group work. The groups are homogeneous in nature. Any functional role within the group such as a team lead or a manager is not explicitly supported by this category of systems in terms of providing capabilities within the system to aid these roles in carrying out their functions and the users assuming these roles cope with this lack of support by either bringing additional tools from outside the system to augment to the system or by interacting with the system in ways not intended by the design of the system. These systems either employ the standard hardware devices thereby implicitly addressing the hardware accessibility issue or assume that the target group has access to the necessary hardware. Hence, we don't see explicit efforts in these systems towards making the system accessible through multiple hardware.

2.2 Different hardware with uniform views

DIVE (Hagsand, 1996) was one of the first CVE to be developed. DIVE allows multiple users to be embodied in a virtual environment and navigate through the environment while communicating with other users over audio, video, text messages, and simple gestures facilitated by avatars. Users can also manipulate objects within the virtual environment. DIVE also supports multiple "worlds" within the virtual environment and users can move between worlds with the help of "portals". DIVE supports multiple hardware devices such as HMDs and conventional desktop workstations. (Daily et al., 2000) present a CVE that uses a distributed software architecture to allow multiple clients to connect into a collaborative session using varying display technologies, to combine an array of different devices like CAVEs (Cruz-Neira et al., 1992), Wall sized displays, and desktop workstations. System enables distributed project teams to take part in a design review process. The changes made to the design at one site are displayed at all clients and the distributed users can participate in the review process by communicating over channels like shared whiteboard, shared browser, and high fidelity audio.

(Mulder and Boscker, 2004) use a special hardware setup to create a desktop AR/VR workspace. The hardware setup comprises a mirror based stereoscopic display and head tracking to provide a shared workspace where two or three users can collaboratively interact with the virtual world that is presented to users through VR and AR individually.

(Pick et al., 2014) present a system that combines Immersive Virtual Reality (IVR) systems such as the CAVE with a lightweight web based counterpart that offers the same functionality and perspectives as the IVR system but in a reduced capacity to facilitate the integration of IVR in the factory planning process. The lightweight application provides a slice of the view that is presented to the IVR users. (Okuya et al., 2018) have created a CVE that allows real time collaboration between users interacting with a wall-sized display and a CAVE-like system to edit CAD data. Even though the system combines two different VR platforms, it presents the same representation of the CAD data through both of these platforms, to the users.

Due to their support for multiple hardware devices, even though these systems present uniform views across those devices, the views perceived by different users vary slightly owing to the affordances of the different hardware devices. However, the software doesn't augment these variations with any additional functionalities such as layering of information. In the same light, the interaction affordances and metaphors of different input devices are factored into the system more to ensure that the users are able to utilize the capabilities of different interaction devices to their fullest extent than to provide support for functionally differing capabilities to different members of the group. However, affordances of different hardware devices themselves make way for certain roles within the collaboration. For example, in cases where a heavyweight hardware system such as a CAVE is paired with a lightweight device such a handheld tablet, the heavyweight counterpart functions as the "command center" allowing the users using it to control and lead the collaborative session. By presenting uniform views to different members of the group, these systems too target groups that are homogeneous in nature. With the exception of (Mulder and Boscker, 2004) the rest of the examples under this category provide support for more than one hardware platform in order to ease the problem of hardware accessibility.

2.3 Uniform hardware with different views

A few collaborative virtual environments have incorporated asymmetric views or perspectives of the virtual world that are presented using similar hardware to different users of the system. CALVIN (Leigh and Johnson, 1996) is one of the earliest systems to present this approach where two sets of users interact with a virtual environment, one set from an in-person perspective, while the other interacts “from above”. This second set of users is presented with a miniaturized version of the virtual environment to create the effect of interacting from above with a scaled model of the environment that the first set interacts with. Avatars are employed to facilitate co-presence. Difference in perspectives enable users to assume different roles in the collaboration. The in-person perspective facilitates finer manipulation of the scene whereas as the exocentric perspective facilitates more global and large scale manipulations. Authors speculate that different views may lead to confusion and suggest that the interface should allow participants to share views and mental models.

A cross-scale CVE presented by (Zhang and Furnas, 2005) allows the users to operate at different scales within the environment by enabling them to dynamically move between different scales. Users begin at the same scale and hence similar views, but can freely change scale at any point. The system is aimed at supporting collaboration in environments that are made up of structures at multiple scales. The authors observe the size related social dominance as a side effect of enabling varying avatar sizes. The author recognize the need to share views and contexts between users at different scales for enabling users to perceive what other are pointing to and propose a few alternative mechanisms to achieve views and context sharing.

Spacetime (Xia et al., 2018) is another system that enables users to dynamically move between different scales while engaged in a collaborative scene editing task. All users use HMDs and controllers to interact with the system where ready-made structures can be placed and transformed. Spacetime addresses level 3 cooperation by means of parallel objects, where for any group interaction resulting in a conflict over an object, multiple copies of the object are dynamically created to resolve the conflict. Spacetime addresses sharing of views between users through parallel avatars where users can place copies of their avatars at different viewpoints and teleport to those avatars and thus get a view of other users' perspective. Differences in perspectives and scales were perceived to be helpful in supporting multiple roles during an expert evaluation of the system. The authors also report that this sharing of views facilitated communication between users.

(Thanyadit et al., 2018) present a CVE to facilitate information sharing between workers working on disjoint tasks with a larger common goal (engineer and interior designer working on construction of a house). The CVE supports remote collaboration and uses 3D stereoscopic display with head and hand tracking. It provides uniform representation of the virtual world for different workers but with different points of view and different layers of information pertinent for each worker. During the evaluation of the system under different collaboration synchronization strategies such as real-time, asynchronous, and so on, the authors found that users experienced confusion while trying to place objects based on their assumption of the other participant's view. The users also relied heavily on verbal communication as they were unsure of whether the other participant's view was updated with the changes they had made.

These systems provide different perspectives to different members of the group and provide functionality that enables different users to make effective use of those difference in perspectives. The differences are brought in mainly to support different roles within the group and additionally to support a combination of individual and group work. Differences in views facilitate different roles, however systems that partition the interaction space based on these differences in views tend to limit or restrict the different roles to users interacting with them. In other words, systems that have specific hardware-software(representation) combinations that remain fixed throughout the collaborative session pose a dependency of roles on the representations and thereby expect the users to remain fixed in their roles throughout the session. Systems like Spacetime that allow users to freely change the representation they are working with allow for flexible roles that can migrate between users during the session.

2.4 Different hardware with different views

(Park et al., 2000) present an exploratory system that allows a group of users to explore oceanographic data using CAVEs and ImmersaDesks (Czernuszenko et al., 1997). The users are presented with a 3D visualization of the data, where individual users can freely create subjective views for personal interaction and analysis. The flexibility to create "local" views is intended to enable different users to have different perspectives of the data and also to foster individual as well as group exploration of the data. Authors observe a need to be able to share views between different users when users were working with local or subjective views to help during coordination and to enhance awareness of each other.

DollhouseVR (Sugiura et al., 2018) is a system that deals with asymmetric viewpoints in the form of a table top surface presenting a top view of the virtual environment while a head mounted display provides an in person view of the same. Although they make use of different technologies to present the two different viewpoints, both of those viewpoints show the same representation of the virtual world. The system is intended for collocated collaboration. Users interacting with different views were isolated to those views meaning each type of user had access to a single type of view which prompted the HMD user to convey spatial details such as width of a walkway using Hand gestures to the non-HMD users, suggesting a need for sharing views between the two types of users. The authors further report that the HMD user would often take off the HMD to get a glimpse of the non-HMD users' perspective, which further points to a need to share views.

MacroScope (Smit et al., 2018) is a mixed reality application that aids in collocated collaboration by presenting a VR user with a first person perspective of an actual physical scale model that other team members in the room interact with. One of the main factors affecting the communication in this setup, as the authors note, is that the other participants cannot visually confirm whether the wearer of the HMD is paying attention to the region of interest in the collaboration at any given point. Further the authors note that immersion led to the HMD users feeling less embodied compared to their non-HMD counterparts in interacting with the model and hence there was a marked difference in the roles assumed by the two types of users. The HMD users took on more of an observatory role thus functioning as some sort of a contractor while the users who were working on the physical model acted more as builders working for him.

(Chenechal et al., 2016) present a system that allows a group of users to collaboratively perform 3D transformations on an object using different sets of hardware devices for display and input for different users (a. 3D stereoscopic display with head tracking and 3D tracked stylus for interaction. b. HMD and two 3D tracked controllers for interaction c. HMD and 2D trackpad for interaction d. Google cardboard or other devices that provide viewing capabilities only) with specific roles. Different users are presented with different perspectives. One user controls translation from a macroscopic perspective of the scene while a second user controls scaling from an inside-out perspective from within the object and they both control rotation. A third user has the same view as the second and can concurrently scale and rotate the object. Other users can view the collaboration using display only devices. By creating different roles based on different hardware setups, the system tries to leverage the interaction capabilities for the actions of different roles in cooperative manipulation.

(Asutay et al., 2005) have created a CVE that enables two remote users to play a game of virtual tennis with each other using a fish tank display (Ware et al., 1993) system and an HMD. The fish tank presents its user with a macro scale of the environment with an exocentric view while the HMD presents an egocentric view. Evaluation of the system reveals that while the egocentric view is better at localizing the user with the environment the exocentric view is better for motion detection. The authors speculate that a hybridization of such systems that can complement each other's weaknesses could prove useful in supporting teamwork.

(Seon-Min Rhee et al., 2003) present a collocated CVE that combines a table top VR workbench equipped with head and hand tracking and a projection wall to facilitate architecture design and simulation. A designer will work on the bench to design. The designed model is simulated on the projection wall, other participants in front of the projection wall can give feedback on the model to the designer.

RoleVR (Lee et al., 2020) is a system that enables collaboration between HMD users and non HMD users by presenting the latter with screen based display and interaction mechanisms to interact with the virtual world. At the same time, the HMD users are also augmented with additional hardware to simulate walking. The system is asymmetric in the views it presents to both sets of users. The HMD users see an in-person perspective whereas the non HMD users see a more macroscopic view of the scene. Evaluation results reveal that presence (engagement) of all users can be improved when role of each user is optimized to the capabilities of the interaction devices thereby enabling active participation of the users in the collaboration. Further, for enhancing presence in the asymmetric environment, it is more important to assign a role to the user than wearing an immersive device like HMD.

SCAPE (Hong Hua et al., 2003) is a collaborative infrastructure that uses Head Mounted Projective Displays (HMPD) and a special room and bench infrastructure created using retroreflective materials to help create visualizations with the HMPDs. The workbench is used to create an outside-in perspective of the dataset whereas the room is used to create an inside-out perspective of the same dataset and individualized views are presented to users based on their viewpoints. The users wear a glove based input device to interact with the scene.

(Roupé et al., 2020) present a Virtual Collaborative Design Environment that integrates a multi-touch table with immersive VR for designing a hospital space. A centralized server maintains a database of all the objects in the scene and keeps all the connected clients in sync similar to the approach I have used. Apart from the multi-touch table and HMDs for immersive VR, the system also supports non-immersive large displays where the users can edit the scene using game controllers. The system allows the scene to be manipulated from any of the connected clients. Despite including three different hardware devices, the system presents the same representation of the scene in all of them, with differing perspectives. Based on a design workshop conducted, the authors observe that the combination of multi-touch table and VR through HMD complement each other by supporting both individual as well as collaborative design spaces and the CVE enables users to transition between shared and individual activities. Also, non-HMD users' awareness of the HMD user's actions within the space proved to be a useful input for the group in assessing the practical implications of their design. In terms of choice of design problem, hardware, and infrastructure setup, the CVE presented by (Roupé et al., 2020) is closest to the prototype I have created. However, the research focus is on ease of integration of the multi-touch table with immersive VR through a cohesive software infrastructure whereas my focus is more on easing any coupling between users and representations.

(Gugenheimer et al., 2017) present ShareVR, a proof of concept collaborative virtual environment designed for living room entertainment keeping both HMD and non-users in mind. ShareVR combines floor projection and mobile displays with positional tracking, to enable non-HMD users to collaboratively interact with HMD users as part of a virtual experience. ShareVR also supports traditional displays to present the virtual scene to bystanders. Authors report that a study conducted to compare ShareVR to a baseline condition showed that ShareVR increased presence, enjoyment, and social interaction of both the HMD users and non-HMD users. While the system combines an asymmetric set of devices, the visual representation of the virtual scene remains the same for all the devices. Moreover, the system assumes the different users to be in similar functional roles within the environment, despite having asymmetry in immersion and interaction modalities.

(Zenner et al., 2019) present two approaches to include bystanders in shared spaces into the virtual experience in the form of immersive notifications and substitutional reality. The idea of immersive notifications is to allow bystanders to connect to the virtual world through their devices such as smartphones to send messages to the HMD user, which are presented to the

HMD user with plausible animations and interactions based on the virtual environment, position of the user within the environment, and so on. Furthermore, to actively involve bystanders in the virtual experience, the virtual world is presented to the bystanders by projecting the virtual substitutions onto their physical counterparts and allows the bystanders to interact with virtual world by using tracked controllers to “point” to objects in the virtuals world through their substitutions. These approaches seem to assume a difference in level of engagement between the HMD users and the bystanders but present the same representation of the virtual world to both the HMD users and the bystanders.

(Thoravi Kumaravel et al., 2020) present TransceiVR, a system designed to facilitate better communication between non-HMD users and HMD users. TransceiVR enables non-HMD users to interact and annotate over the virtual scene in real time using a 2D display such as a handheld tablet and uses depth map to accurately place the annotations in the virtual world for the HMD user to make sense of the annotations. Although TransceiVR presents the same representation of the virtual world to both HMD and non-HMD users, it assumes a difference in roles of the two types of users.

(George, 2019) investigates methods to enable better communication between HMD users and bystanders especially to allow bystanders to interrupt VR users without adversely affecting the presence of the VR user. As potential solutions towards this end, the author notes external screens and screens on the back of the HMDs to relay the cognitive load of the VR users to the bystanders to help them decide when to interrupt the VR user.

This category of systems enable different roles in groups similar to the previous category but the support of different roles is more pronounced by the asymmetrical nature of the devices due to different interaction metaphors that are supported by those devices. Some of the examples in this category such as (Chenechal et al., 2016) and (Asutay et al., 2005) make the component devices complementary to each other in their functionalities where as others such as (Roupé et al., 2020) make the same set of functionality available through all the participating devices. The former systems restrict specific roles to users interacting with each of the different devices due to this splitting of functionality between the different components whereas the latter group of systems allow for flexibility of roles and enable roles to migrate between the users over the duration of the collaboration.

2.5 Summary

Figure 1 summarizes the research challenges addressed under this categorization of CVEs based on hardware and software (views/perspectives) variability.

2.6 Research on roles and asymmetric collaboration

(Strijbos et al., 2005) while investigating the differences between functional roles (roles with a predefined set of responsibilities within the group work) and spontaneous roles (roles that emerge on their own during the group interaction) report that members who assume roles (functional or spontaenous) in group work tend to perform more responsibilities associated with the role than members who do not assume any role. Further, they note that with time, the spontaneous roles may shift between members of the group.

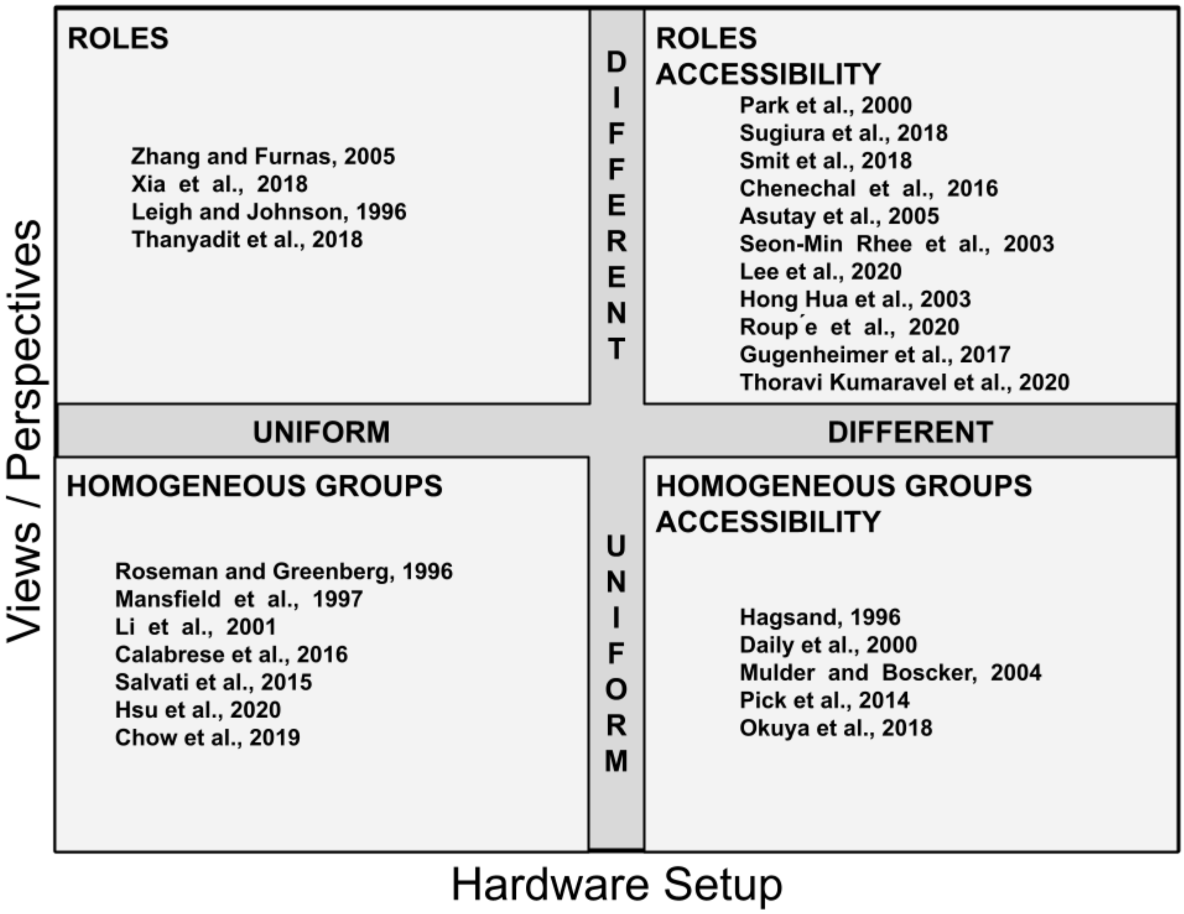


Figure 1: Group needs addressed by hardware and software configurations in CVEs

(Cummings and Kiesler, 2008) note that people in the same discipline will share tools that others do not use. That is, people from multiple domains come with a background of their own set of tools, representations, ways of interpreting a piece of information and so on. This results in reluctance to using tools that are unfamiliar to them. Moreover, the interpersonal relationship between interdisciplinary collaborators is more of a partnership than complementary. The authors further note that differential use of technology such as only a few members of the group having access to a specific hardware could become a barrier to interdisciplinary collaboration.

(Graham et al., 2013) created an asymmetric collaborative setup involving a multi-touch tabletop display and a laptop with game controller allowing for simultaneous orchestration of a game by one user while it is being played by another. The one way sharing of player's view with the orchestrator coupled with game editing capabilities resulted in the orchestrator assuming several behavioral roles such as shepherding the player, collaborating with the player, playing silent adversary or architect to assist the player and so on. Several interpersonal interaction styles were also reported such as orchestrator dominant, player driven and so on that illustrates support for flexible group dynamics through asymmetry.

2.7 Lessons Learned

Here I list some of the lessons learned from these different systems that are relevant to my research:

- Multiple perspectives and functionalities that complement those perspectives facilitate different users within the group to assume different roles. (Sugiura et al., 2018) (Lee et al., 2020)

- The two main ways in which perspectives differ is through information layering and difference in viewpoints. (Park et al., 2000)
- When presenting multiple perspectives, sharing of views is seen as an important tool to aid in helping coordination and awareness. (Park et al., 2000)
- In asymmetric systems, apart from multiple perspectives, the differences in interaction capabilities of different devices enable multiple interaction metaphors. Such combination of metaphors can be useful in supporting different roles within the collaboration. (Chenechal et al., 2016) (Smit et al., 2018)
- Sharing of HMD user's view with the non HMD counterparts in an asymmetric collaboration aids in improving coordination as well as communication.(Smit et al., 2018) (Roupé et al., 2020)

2.8 Gap in research

In the explored literature space, the examples that present different views to different users with the intention of providing support for different roles are the most relevant as systems that are comparable to my research. However the gap between my research and this set of examples is that their research is directed at supporting different functional roles, whereas I incorporate a few of the lessons learned from these systems into the design of my prototype, thus taking those lessons as the starting point and focus my research on a specific challenge that none of these systems have addressed: *In a hybrid collaborative setup how to mitigate the effects of representation dependency?*

TABLE I: Systems that support multiple views or perspectives (S: Single type, M: Multiple types, S/M: Single or Multiple type(s)

Sl No	Research	Display Devices	I/O Devices	Views or Perspectives	Visual Representations	Roles	Level of cooperation (Margery et al., 1999)
1	(Leigh and Johnson, 1996)	S/M	S	M	S	M	2
2	(Park et al., 2000)	S	S	S/M	S	S	2
3	(Zhang and Furnas, 2005)	S	S	S/M	S	S/M	2
4	(Chenechal et al., 2016)	M	M	M	S	M	3
5	(Thanyadit et al., 2018)	S	S	M	S	M	2
6	(Sugiura et al., 2018)	M	M	M	S	M	2
7	(Xia et al., 2018)	S	S	S/M	S	S/M	3
8	(Roupé et al., 2020)	S/M	S/M	S/M	S	M	2
9	(Gugenheimer et al., 2017)	M	M	M	S	M	2
10	(Thoravi Kumaravel et al., 2020)	M	M	M	S	M	2

Of the surveyed CVEs, Table I shows a list of systems that are closest to my research. The table provides comparison between my research and these existing systems across a few key attributes. An S (for single) indicates the design of the CVE supports a single type of the attribute, an M (for multiple) indicates the design of the CVE necessarily assumes the existence of more than one type of the attribute, and an S/M indicates the design supports flexibility in having either a single type of the attribute or more than one type. I have focused on these distinctions of S, M, and S/M across the different attributes since my research is centered upon mitigating the effects of representation dependency.

Table II shows a list of some of the commercially available CVEs to provide a similar comparison with my research. These systems focus on different collaborative work scenarios such as meetings, architectural and engineering design reviews, and so on. A common thread across all these systems seems to be that they focus on bringing geographically distributed groups together by providing them a virtual space equipped with virtual tools necessary to

TABLE II: Commercially available CVEs

Sl No	CVE	Display Devices	I/O Devices	Views or Perspectives	Visual Representations	Roles	Level of cooperation (Margery et al., 1999)
1	Spatial	S	S	M	S	S	2
2	Vizible	S	S	M	S	S	2
3	The Wild	S/M	S/M	M	S	S	2
4	Techviz	S/M	S/M	M	S	S	2
5	MeetinVR	S	S	M	S	S	2
6	Virbela	S	S	M	S	S	2

collaborate. While some of them allow different users to connect to the virtual world using different devices, they present the same visual representation of the virtual space to all the users of these systems and don't seem to explicitly facilitate differences in roles among users.

CHAPTER 3

HYBRID COLLABORATIVE VIRTUAL ENVIRONMENT

[*This chapter was previously published as part of (Bharadwaj and Johnson, 2020)*]

The hybrid collaborative virtual environment consists of three different applications, namely a 2D application, a 3D application, and an immersive VR (Virtual Reality) application, all interacting with a virtual environment for architectural planning. All three applications are synchronised using a centralized server to enable real time remote collaboration between them. The 2D application presents a monochromatic top view of the scene over a grid layout. The 3D application presents an in-person perspective of the scene with a limited field of view. The VR application presents a fully immersive 360 degree view through the HMD to the user interacting with it. For this prototype, I chose a basic set of elements like Walls, Doors, Windows, and Furniture to provide enough interaction possibilities for evaluating the prototype. All the three applications are complete in their own right, in the sense that they can be individually used to create architectural designs. All functionalities concerning architectural design creation such as the creation of walls, creation and manipulation of furniture, and so on have been implemented in all the three different interfaces.

3.1 Functional requirements for an architectural design application

All the three different applications should incorporate all the functional requirements for editing the architectural design. Here I briefly describe these requirements to help the reader understand the implementation details of the different applications that are explained below. I decided to have a basic set of four types of elements as the building blocks of the design space. They are walls, doors, windows, and furniture. Walls have a fixed height and thickness, but variable lengths and can be placed anywhere within the scene. So it would suffice for any application facilitating creation of walls to provide the users a way to specify the start and end points of the wall. Doors and windows are functionally very similar to each other, in the sense that they are both units that are placed within the walls, have fixed shapes and sizes, take on the orientation of the wall within which they are placed, and can be placed anywhere throughout the length of the wall as long as they stay entirely within the bounds of the wall length. To facilitate creation of doors and windows, an application must ensure that once created, a door or a window must only take on a point along the length of a preexisting wall as its valid stationary position, and have its y-axis rotation in line with that of the wall. Furniture objects such as couches, tables, chairs, and so on all have fixed shapes and sizes. Interaction with furniture thus gets limited to changing the position and y-axis rotation of a piece of furniture.

3.2 Architecture

SAGE2 exposes an API for creating custom applications. I developed the 2D and the 3D applications as SAGE2 apps to leverage the multi-user interaction capabilities that SAGE2 offers. This makes it possible for more than one user to simultaneously interact with these two applications, thus enabling collocated collaboration. SAGE2 allows multiple users to interact with applications on a large display using their personal devices such as laptops. Multiple users can simultaneously access its web application to connect to the large display and interact with

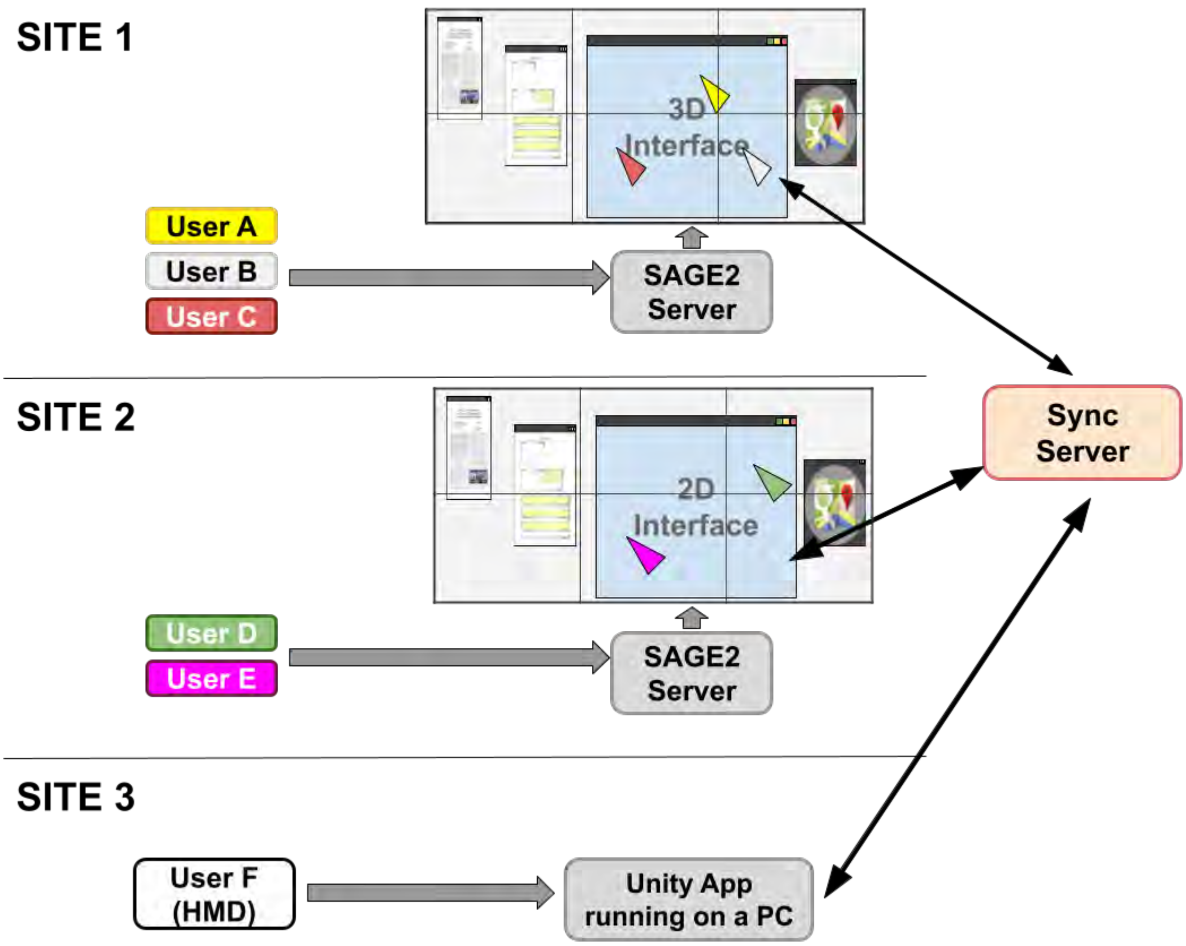


Figure 2: Architecture of the collaborative setup showing one instance each of the 2D, 3D, and VR applications

it. By making the 2D and the 3D applications be custom applications on top of SAGE2 I let SAGE2 handle multi-user interaction for 2D and 3D applications. As shown in Figure 2, I developed a synchronization server that relays messages between all the instances of the three different applications and keeps them updated and in sync. Every action of each client such as moving a piece of furniture, deleting a wall and so on is conveyed, in real time, to all the participating clients. Further, the pointer location of the users at the 2D application, the camera location and orientation of the 3D application, and the head location and orientation of the VR users are all conveyed to all the clients in real time as well. Thus any action performed at any client is immediately replicated at all the clients. The position (and orientation) information of different users are used to animate their corresponding virtual representations at all the different clients. This allows users to know where "within" the scene, each user is and what they are doing at any given point in time.

3.3 2D application

The 2D application has been implemented as a SAGE2 custom application in order to leverage the affordances provided by the SAGE2 platform such as scalable resolution and simultaneous multi-user real time interaction. The 2D application as shown in Figure 3, has a grid layout with each grid block representing 1 foot. These grid lines along with the rulers on the border depicting the foot units of the lines are meant to serve as guides to the users for placement of objects within the scene. A menu button has been provided on the top left corner but can be moved around (to avoid occlusion of the grid space) anywhere within the layout of the application. As shown in Figure 4, the menu contains options to create walls, doors, win-

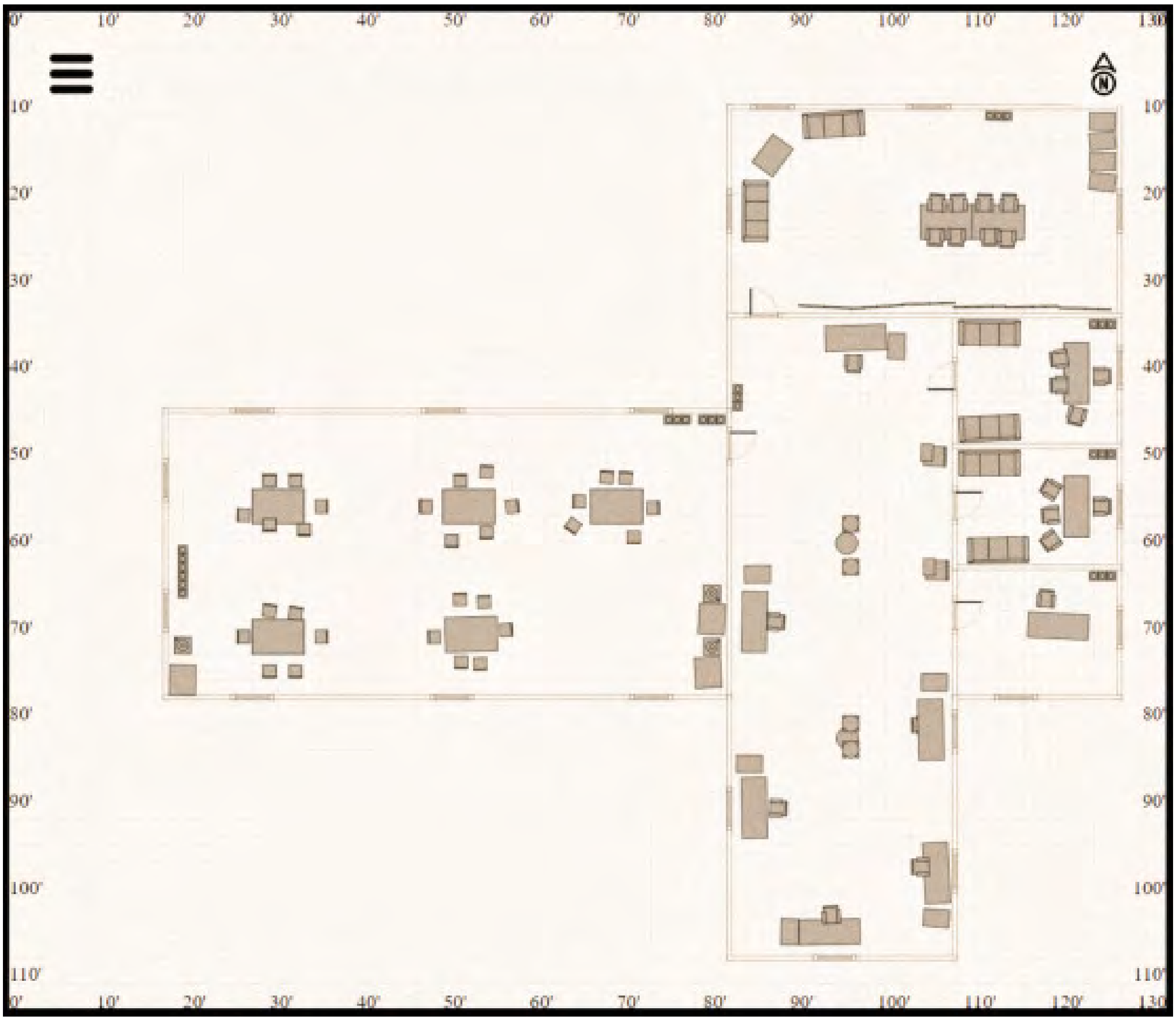


Figure 3: 2D application showing the floor plan of an office space.

dows, furniture objects, and flags. A contextual "help" text appears on the bottom left corner of the layout, to guide the users with information about the possible next steps that the users can take when interacting with either the objects in the scene or during one of special modes. The layout can be zoomed in and out enabling the users to work at a scale that is comfortable to them. A user would interact with the 2D application using the left mouse button, scroll inputs, and keyboard inputs. In the 2D application by default, users will be in "Selection" mode. In this mode, a user can "select" objects in the scene by clicking on them, for continued interaction with the selected object. For example, in case of furniture, the selection allows the users to move around, rotate, or delete the piece of furniture from the scene. When a user is in a different mode such as the "Wall Creation" mode, the user can get back to the "Selection" mode by clicking on the "Selection" mode icon from the menu. To create a wall, users can click on the wall icon from the menu. This makes the user enter the "Wall Creation" mode. This is indicated in the help text as "click to start wall". Now, a click anywhere on the grid initiates a new wall. The point of click is mapped to the nearest grid point and that grid point is used as the actual starting point of the wall, to get the effect of snapping to the grid. The current mouse position becomes the ending point of the wall, resulting in a "rubber band" wall fixed on one end and moving with the mouse pointer on the other end. A second click fixes the ending point of the wall to the location of the click (mapped to the nearest grid point), thereby completing the wall creation. To facilitate quick creation of adjoining walls, this end point of the wall is also treated as the starting point for a new wall. A user can easily break this chain

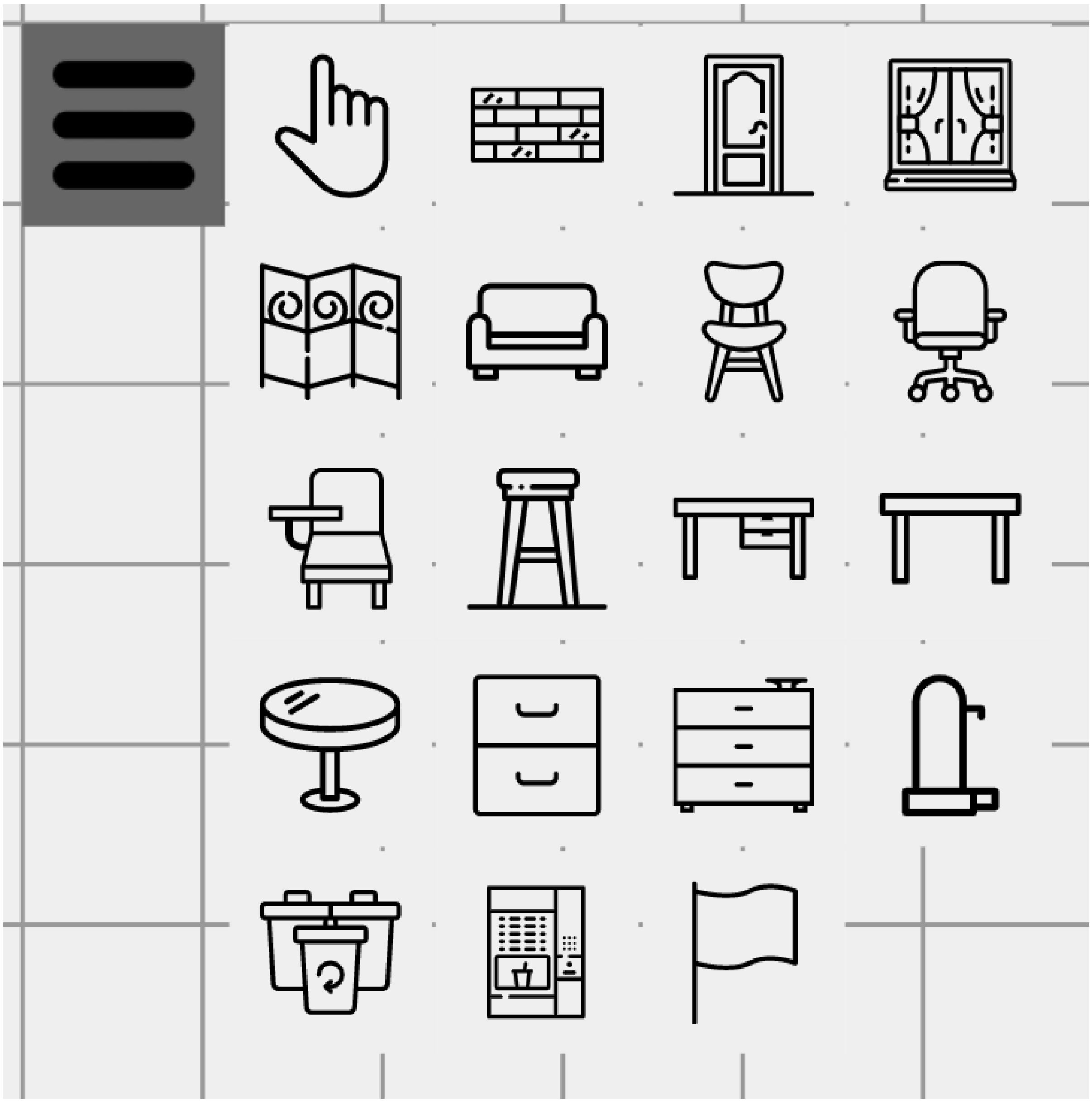


Figure 4: Menu

by using a designated key to remove the current wall (rubber band wall). The user remains in the "Wall Creation" mode and can continue to create new walls.

To create a door or a window in the 2D application, users can click on the respective icon in the menu and a corresponding item gets attached to the user's pointer and starts to move with the pointer. A user will now be in "Door or Window" mode. When a user hovers the pointer on a wall, the attached door or window orients itself in line with the wall as a way of providing feedback to the user that that is a potential "drop" point for the door or window. At such a location the user could then make a single click to fix the door or window at that point on the wall. A click anywhere else other than on a wall has no effect, and the new instance of door or window continues to be attached to the user's pointer. If the user decides not to place the item on any wall, a designated key press can be used to remove the attached item from the pointer, bringing the user out of "Door or Window" mode. To create a piece of furniture in the 2D application, users can click on the respective icon in the menu and a new instance of the chosen piece of furniture gets attached to the pointer and moves with it. A click anywhere on the layout will "drop" the new piece of furniture at that point.

To change the position of a previously placed door or window, users can "pull" the instance from its location on the wall by performing a mouse down and a slight drag. This action results in the instance of door or window getting attached to the mouse pointer, thereby bringing the user to "Door or Window" mode. Now the user can place it at a new position on a wall anywhere within the layout or discard it, as explained above. To move a piece of furniture, users can perform a mouse down and a slight drag on the piece of furniture in question. This attaches the piece of furniture to the mouse pointer. Now the user simply “drops” it off at a new position with a click of the mouse at the desired position. To change the orientation (rotate) of a piece of furniture, users can “select” it as explained above and using designated keys on the keyboard, can rotate the piece of furniture along its y-axis. To remove an object (wall, door, window, or furniture) from the scene, users can “select” it as explained above and then use a designated key press to remove it from the scene.

Flags are special objects that can be used as points of reference within the scene. They can be used to draw different users' attention to a part of the scene. Creation of flags follow the same process as pieces of furniture explained above. The flags are shown in the 2D application as colored circles as shown in Figure 7a. The color of a flag is chosen randomly by the application from a predefined set of colors. A flag's color is shared across all sites thus allowing it to act as a point of reference within the scene. Any user from any site can refer to a flag by its color and the other users will be able to unambiguously and accurately infer where within the scene the flag is.

3.4 3D and VR applications

The 3D application presents the users with an in-person perspective of the scene, rendered on a large display in a rectangular window as shown in Figure 5, whereas the VR application presents the same in-person perspective in a fully immersive head mounted display as shown in Figure 6. The scene itself consists of a floor laid with grid lines for aiding the users with placement of objects. A menu, identical to that of the 2D application both in appearance as well as functionality, is provided in the 3D as well as the VR applications. Both of these

Figure 5: Two users interact with the 3D application

applications also have “Selection”, “Wall Creation”, and “Door or Window” modes similar to the 2D application, albeit with interaction metaphors that are more appropriate to 3D interaction. For example, unlike the 2D application, newly created pieces of furniture do not follow the pointer, and are placed in front of the camera and the VR user respectively. Users can then “pick” them up and move them around.

Similar to the 2D application, a user would interact with the 3D application using the left mouse button, scroll inputs, and keyboard inputs. The 3D application allows the users to navigate through the scene by mapping the mouse scroll to forward and backward movements of the camera within the scene and designated keys for turning left and right. A user would

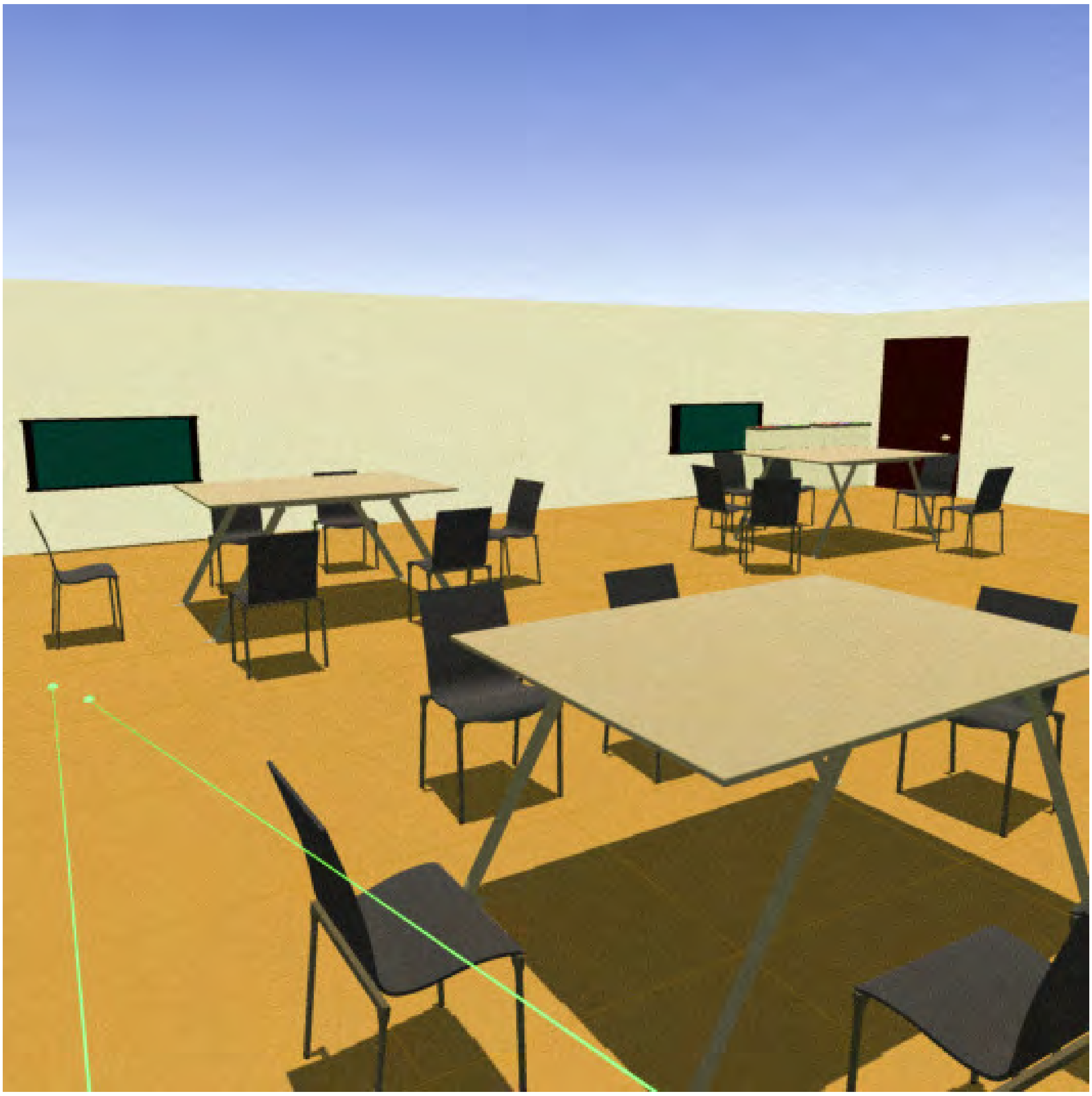


Figure 6: VR View of a part of the designed space

use the VIVE controllers (hand held) to interact with the VR application. The VR application allows the user to freely look around and walk within the scene as well as teleport to any point within the scene. Flags are presented as tall (40ft) colored pillars within the scene in the 3D and the VR applications as shown in Figure 7b and Figure 7c. This is to help users to see the flags despite being behind walls and other structures that might occlude part of their view. Additionally, flags in the VR application act as teleportation targets. This allows the VR user to easily reach a flag despite being anywhere within the scene, since the flags are tall and can be seen even from a distance and even when the user is behind any structure or objects in the scene.

The 3D application is designed on the metaphor of being a “window” into the virtual world. When multiple users interact with the 3D application, they will all be able to interact using their own pointers and are able to grab and move different objects in the scene simultaneously, however more than one user can’t grab a single object and move it simultaneously. A single menu has been given and this menu can be interacted with by any single user at a given time to create an object. In case of the 3D application, moving about within the scene is shared between all the users interacting with the application. In other words, scroll and arrow key events from any of the users interacting with the application will cause the camera to move and rotate respectively. However, while one user is moving the camera, other users can create new objects, and interact with objects in the scene. The 3D application is showing as a rectangular “window” to other users in the scene and in that sense all users interacting with the 3D application share a common avatar, however, rays are cast into the scene from the point of each user’s pointer location on the 3D application to show where each user is pointing at or what object each user is interacting with.

The 3D application has an overview map that allows the users to quickly and easily get an idea of the entire scene as well as where within the scene, the other participants are. This makes up for the comparatively slower navigation of the 3D application within the scene (the "drive through the scene" metaphor of the 3D application is relatively slower than the VR users' ability to teleport instantly to any part of the scene or the 2D application users' ability to see the whole scene at once and "be" at any point within the scene by simply moving the mouse pointer over that location on the grid). In this way, when a location or an object within the scene is referred to by the other users, giving some description of the location or a reference point such as a flag, whereas the VR users and 2D users "navigate" to the point as part of the collaborative exchange, the 3D users can make sense of the reference with the help of the overview and thus still be able to meaningfully participate in such a collaborative exchange.

3.5 Representations of different users within the scene

In a typical collaborative virtual environment co-presence of different users is achieved by representing users as avatars. This makes sense when all the users are fully immersed in the environment and also have the same interaction affordances. However, in a hybrid system like ours, different users have different levels of immersion and affordances of different applications impose differences in how they interact with the scene. To achieve meaningful co-presence and to facilitate effective communication in such a case, any representation of a user should reflect these differences. Keeping this in mind I created representations as follows: The 2D application

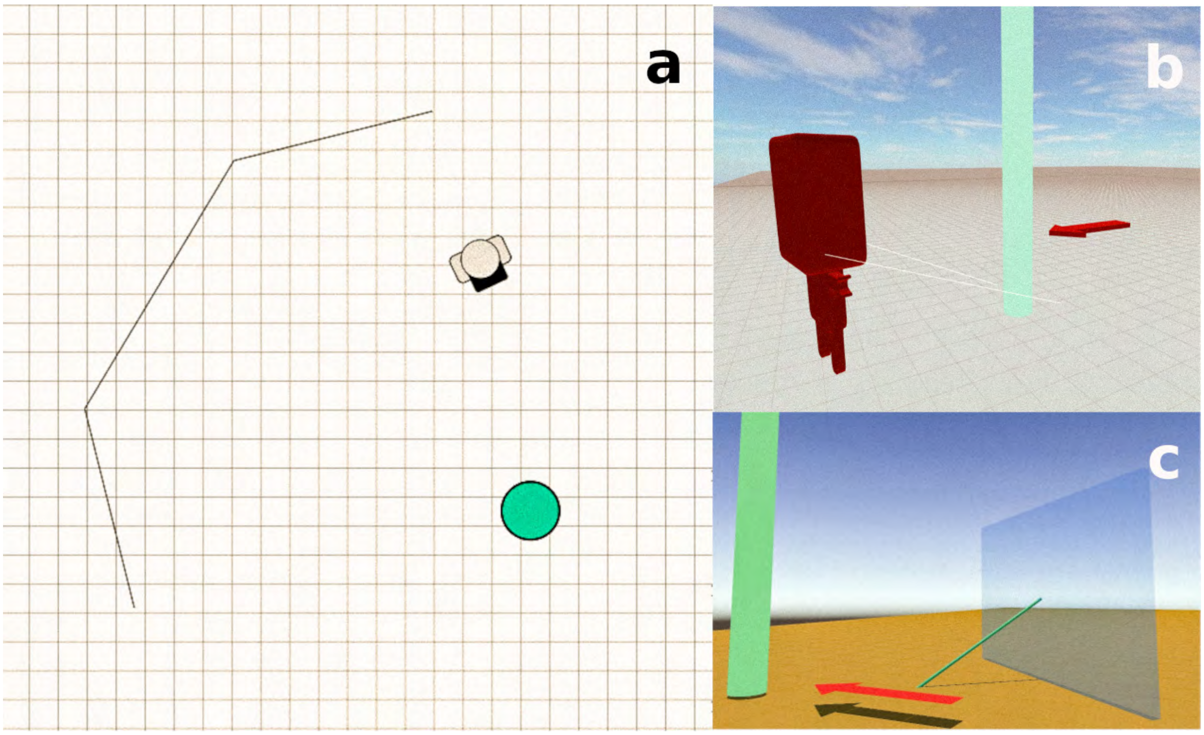


Figure 7: a. 2D application showing 3D user and VR user and a flag. b. 3D application showing 2D user's pointer as an arrow and VR user as an avatar with the same flag shown as a column. c. VR application showing 2D user's pointer as an arrow and 3D user as a 3D window with a pointer coming out out of it and the flag shown as a column

serves as a top view and this is reinforced in the way the VR user as well as the 3D application's camera within the scene are depicted in the 2D application as shown in Figure 7a. The VR user's representation shows a human icon wearing a VR headset, from the top view. The camera of the 3D application is shown as a straight line with bent edges indicating a "window" in to the scene with a limited field of view. At the 3D and VR applications, the mouse pointers of users from the 2D application are represented using 3D arrows in the scene and they continuously move about within the scene (similar to the "God-like" interaction technique (Stafford et al., 2006)) following the pointer movements of users within the grid of the 2D application. The VR user is represented as an avatar (Figure 7b) in the 3D application, with two rays attached, that reflect where the VR user is pointing the controllers. The camera of the 3D application is represented as a rectangular window in the VR application (Figure 7c). Whenever a user at the 3D application has their pointer on the application window, a ray is shown as coming out of the window, enabling others in the scene to identify where the user is pointing to. That is, the pointer location of users are used to cast rays from the camera into the scene, and this is shown to other users in the scene.

CHAPTER 4

PRELIMINARY USER STUDY

[*This chapter was previously published as part of (Bharadwaj and Johnson, 2020)*]

To get an idea of the general usability of the prototype system and to gain insights into how the differences in representations across the applications affect the group work, I conducted a group user study. In the study I asked a group of participants to use all three of the applications to collaborate in designing an office space.

4.1 Method

The study consisted of 5 trials (and two mock trials prior to the actual study to catch any interaction issues with the applications), with each trial involving 4 participants. One participant interacts with the 2D application, and one interacts with the VR application through an HMD, and two participants interact with the 3D application. The participants were randomly assigned to these applications, however I made sure that the participant assigned to the VR application was not prone to motion sickness and was comfortable with using VR technology. Once assigned, the users were restricted to using that particular application through the respective hardware for the duration of the study. These assignments were made prior to the training session and all participants trained only on the application they were going to interact with for the rest of the session. Even though both 2D and 3D applications are capable of handling multiple users in a collocated collaborative manner, due to lack of availability of participants I decided to limit collocated collaboration to only one of those applications in the study. Each application was situated in a different room within our lab to reflect a real remote collaboration scenario. 3D application was presented on a 23.8 foot × 6.7 foot (7.25 m × 2.1 m), 37.3 megapixel large display running a SAGE2 instance. The display was situated in a 41 foot × 24 foot (12.5 m × 6.4 m) room. 2D application was presented on a 13.4 foot × 5.7 foot (4.1 m × 1.74 m), 12.6 megapixel large display running a SAGE2 instance. The display was situated in a 41 foot × 28 foot (12.5 m × 8.53 m) room. The participants were seated in front of these large screen displays and interacted with them using laptops. In a third room, the VR application was presented using an HTC vive HMD (display resolution: 1080×1200 per eye (2160×1200 combined pixels), refresh rate: 90 Hz, field of view: 110 degree). The VR user had a 10 foot × 10 foot (3.05 m × 3.05 m) space to walk around. All three locations were connected through an audio conference and participants could speak to each other throughout the study. The participants were given a brief practice session at the beginning of each trial to introduce them to different functionalities of the application they were going to work with and to familiarize them with co-presence, tele-pointing, and communicating with each other. After undergoing the practice session the participants were given a set of high level requirements to design the office space such as, “A conference room that can host 8 people”, “An open floor area to seat 4 employees”, and so on. I did not pose any requirements on who should perform what task and that was left entirely up to the group to decide during the session. I set a time limit of 75 minutes to give the participants enough time to work, however they could finish earlier. The participants were informed about the time limit at the beginning of the session. Every session

TABLE III: Average scores of metrics for usability, co-presence awareness, and ease of collaboration (on a scale of 1-5 with 1 being the lowest score and 5 being the highest score)

Metric	2D application	3D application	VR application
Scene Navigation	4.3	2.7	3.2
Object Creation	4.4	4.1	4.4
Object manipulation	4.2	2.6	3.2
Locating others users within the scene	5.0	4.1	3.8
Tell where other users were looking or pointing	4.6	3.9	3.6
Tell what objects others were interacting with	4.2	3.5	3.4
Tell what interactions others were performing	4.0	3.5	3.0
Draw other users' attention	4.8	4.3	4.4
Communicate	4.3	4.3	3.8
Convey Ideas	4.6	4.7	4.2
Collaborate	4.3	4.3	3.6
Complete the task	4.6	5.0	5.0

was audio and video recorded. Additionally, I recorded the head orientation of the users at the 3D application to see where each user was looking at (looking at the 3D application, looking down or away from the display and so on) while working on the task. Since I did not perform any quantitative analysis on the different phases of collaboration: refer Section 4.3, even though I collected the head orientation data, I did not use that data. Also, every action of each user was logged capturing details such as their location in the scene at the time of the action and the object/s in the scene that the user interacted with, in taking that action. A brief survey was administered to the participants at the end of the session.

4.2 Results

I asked the participants to fill out a survey at the end of the user study session. The survey contained a set of questions aimed at getting an idea of the general usability of the prototype

TABLE IV: Total duration and summary of objects created and edits in the scene

Trial	Time to completion (in min)	Objects created	Total edits
1	34.5	135	118
2	52.8	261	174
3	38.2	185	146
4	29.5	138	90
5	68.0	286	139

including its affordances for group communication and collaboration. Table III shows the results obtained from the survey. While the results indicate that the participants were fairly satisfied with its usability, relatively lower scores were reported for the 3D application on navigation and object manipulation metrics. I had also asked descriptive questions towards understanding any issues the participants might have had in interacting with the system. Some of the answers I obtained helped me understand those lower scores. On a few occasions when the view had too many closely placed objects, the 3D application made it difficult to accurately select objects. The navigation difficulty was also reported when the view had too many objects. This is mainly due to the object picking algorithm that I implemented at the 3D application and has been fixed since the running of the user study. The different representations of different applications to achieve co-presence did not impede the collaboration as we can see from the results. In fact, I noted through the video recordings of the sessions that the users very quickly became accustomed to how others perceived the space and how they interacted with the scene.

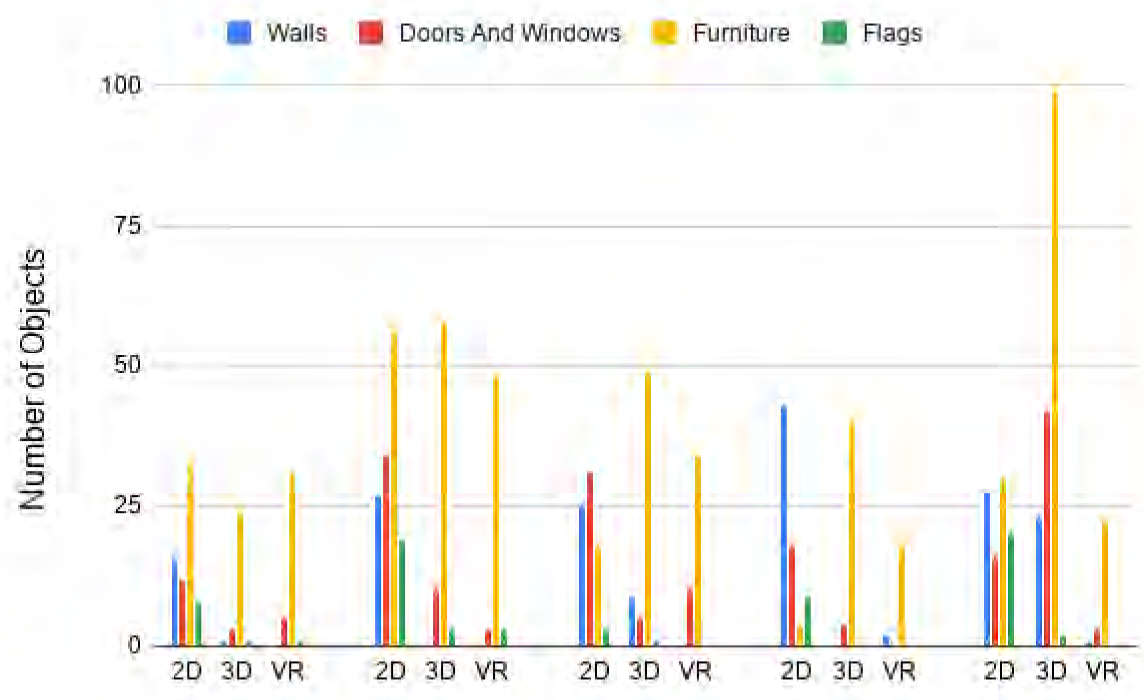


Figure 8: Break down of all the design objects created by different participants

Table IV gives a summary of the interactions in each trial along with duration of the trials. This data shows the participants interacted quite a fair amount with the system and thus further supports the subjective scores from the Table III

The chart in Figure 8 shows a breakup of all the objects that were created by different participants (I combine the numbers of both the collocated participants at the 3D application, as the same affordances apply to both of them) of all the trials. As can be seen in this chart, except for the fifth trial, in every other trial, the walls were mostly created by the 2D application. Through the recording I observed that, at the beginning of each trial the participants briefly

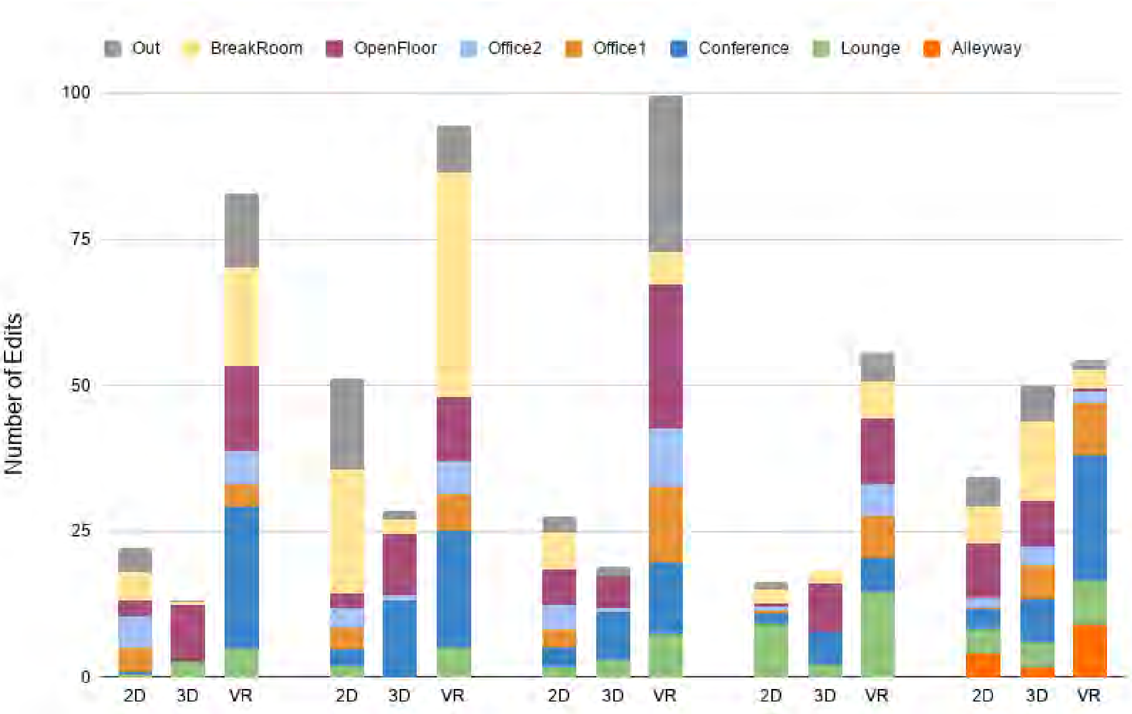


Figure 9: Break down of edits done by different participants at different locations (Out refers to outside the boundaries of the floor plan)

discussed how to proceed with the task, and in the first four trials, the users felt that large wall creation was easier for the participant interacting with the 2D application. I also noticed that, soon after creating the walls, the participants at the 2D application would proceed to place the doors and windows on them. This can also be noted from the break down shown in Figure 8

I noted all the different interactions (edits) that participants had with different objects that they created in the scene throughout the session. Since these edits constituted a major part of the total work done I used the logs to find the break up of these edits based on “location” within the design space such as “Lounge Area” and so on. Figure 9 shows the results. I note two things from this break down. First, in some cases one of the participants worked almost entirely on particular parts of the space, for example, the VR user from trial 1 working solely on the conference room, whereas in certain cases such as in trial 5, all the participants shared the work in creating the conference room. Second, VR participants generally did more interactions. When seen together with the 2D participants mostly creating walls, the results suggest that task division is guided by the affordances of the different applications.

4.3 Observations

All the participants took the task given to them seriously and tried to thoroughly apply themselves to working on the task. Figure 11 and Figure 10 show a couple of examples of spaces that were created during these trials. These examples show that the participants took the task seriously and worked on it. From the video recordings of the sessions, I observed a few elements of the collaborative exchanges that happened between the participants. First, there are five phases in which participants interact with the system and with each other. They are:

1. Interaction with application to achieve some action like creation or moving an object in the scene.
2. Planning the next steps in the task through Discussion.
3. Task related Communication.
4. Review of an action or a sub task performed.
5. Comments and queries unrelated to the task (includes communication about the application, general conversations. . .)

Second, by the end of the practice session the participants concluded that certain aspects of the applications made it easy for performing particular roles within the collaboration and took this into account in working as a group. In every trial, the participants at the 3D application took charge of leading the sessions. That is, they would assign different tasks to the other participants. For example, asking the 2D user to create walls, or asking the VR user to give feedback on a part of the designed space. I feel that this was largely due to the availability of an overview map, in addition to the in-person perspective for the 3D users, which gave them an advantage to choose between the two views that other two users had singly. This made them feel more in control to drive the session. Third, even though all applications are equipped with all the functionalities needed to complete the task at hand individually, the affordances of the different applications favored particular applications for specific functionalities. As seen in the results, wall creation was perceived to be easiest for the 2D participant. The VR users were favored by the other participants for review of designed parts of the spaces, as they realized that realistic assessment of spaces was better done through VR. I noted several instances in these sessions where one of the other participants would ask the VR participant to give feedback on a part of the space that they had finished designing. They would place a flag at the location that they had worked on and notify the color of the flag to the VR user. The VR user would then quickly teleport to the flag, take a look around, comment on it, and go back to doing whatever they were doing. Fourth, having different representations did not impede the collaboration: Users were able to easily understand what a user was referring to whenever that user drew attention of others to some object within the scene. The recordings show that an average of 22 times (per session), users tried to draw the attention of each other to some object in the scene and this was immediately (less than 2 seconds) followed by an acknowledgement for their call and a response that confirmed to us that the other participants had correctly identified what was being referred to. Also, except for one trial, all the others made liberal use of flags (as seen in Figure 8) to either draw each others' attention or to help others to navigate to a location. All these points help to reinforce my initial assumption that combining different applications with heterogeneous representations does not negatively affect the collaboration, but helps in making the group work more flexible.

Figure 10: Office space created in one of the trials

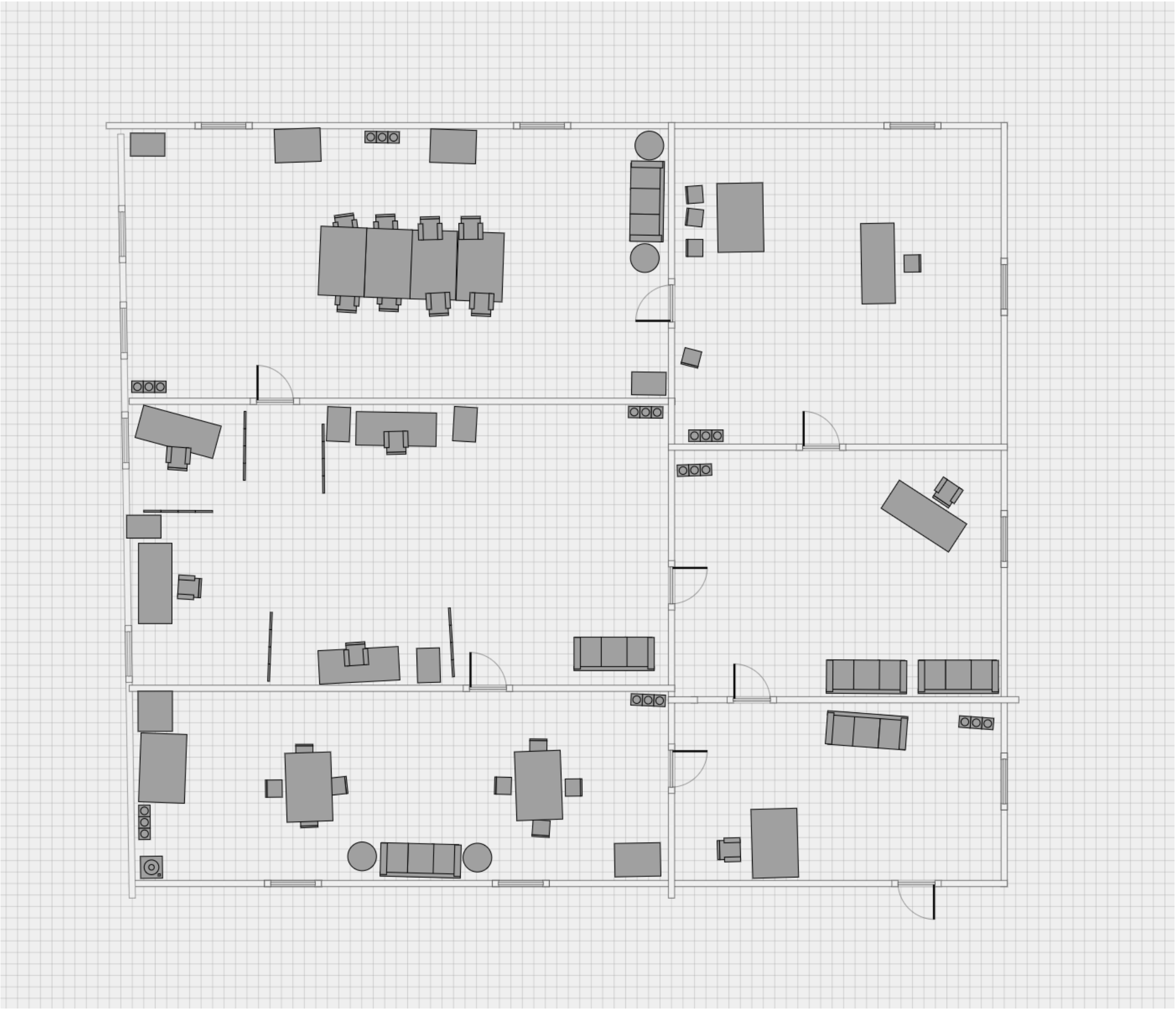


Figure 11: Office space created in one of the trials

CHAPTER 5

INTEGRATION OF A HIGH RESOLUTION LARGE DISPLAY ENVIRONMENT WITH THE HYBRID COLLABORATIVE ENVIRONMENT

With a research interest in exploring the challenges that are present in supporting interdisciplinary collaboration through CVEs, I created a prototype for architecture design as a hybrid of three different applications. I conducted a preliminary group user study of the prototype to gauge the usability of the prototype and to explore the challenges in supporting interdisciplinary collaboration. The study revealed that during the collaborative session the users counterbalanced what they perceived as limitations of one application with the affordances of another application. Further, limiting users to interacting with one application each led to the formation of spontaneous roles that were forced due to dependency on application or representation. Since large displays are known to support multitasking I believe that they can be effectively employed in the collaborative setup to integrate shared views and shared interactions into the collaborative setup to address the representation dependency issue. This led to the four research questions detailed in the next section. Hence to answer these research questions, I integrated a high resolution large shared display environment into the hybrid collaborative setup to create a shared interaction space. In this shared interaction space the non-HMD users have quick and easy access to the views of all three applications and they are able to freely move between interacting with either of the 2D and 3D applications.

5.1 Research Questions

1. **How will the integration of shared views and shared interactions with the hybrid CVE affect group collaboration in such a hybrid CVE? Specifically, how will the integration affect the formation of spontaneous roles that are influenced by dependency on representations in such a hybrid CVE?**
2. **Will the integration improve the transparency of the collaborative environment?**
3. **Will the integration make it easier for the group members to communicate with each other?**
4. **Will the integration improve the work share between the group members?**

5.1.1 Work share

One of the research questions focuses on the work share between participants. As it is not a well known term, I define work share here with respect to collaboration.

Collaborative work comprises of not just the interactions the group members have with the collaborative tool or environment, but also the interactions they have with each other by means of communication. If we take every action a user performs as well as every bit of communication a user generates as a unit of interaction, then we can say that the total work done during the collaboration is the sum total of all such interaction units generated during the collaborative session.

Work share of each user then simply is the share of interactions out of the total, that is generated by the respective user. An equal work share among the participants of a group collaboration would generally suggest that all members of the group contributed equally to the collaboration and is thus desirable.

5.2 User Study

5.2.1 Purpose of the study

I conducted a formal user study to analyze the effects of integrating shared views and shared interactions, using a high resolution large display environment, with the hybrid CVE prototype that I created. The study was designed to compare collaborative sessions performed using just the hybrid CVE in a collocated setting with collaborative sessions performed using the hybrid CVE integrated with shared views and shared interaction, using a high resolution large display environment in a collocated setting. This study was conducted in a collocated setting unlike the preliminary study which had participants spread across three different rooms. This change became necessary to minimize the number of people (participants and research personnel) involved in each trial due to the pandemic.

5.2.2 Method

Each trial involved three participants. In each trial, one of the participants interacted with the VR application using an HTC Vive head mounted display. The other two participants interacted with the 2D and 3D applications on a high resolution large display. In order to evaluate the effects of integrating a high resolution large display environment with the hybrid collaborative setup, the study was designed to consist two variations of the collaborative setup:

- Individual Interaction Mode (IIM): In this mode the high resolution large display area was partitioned into two halves with two separate instances of SAGE2 controlling each half of the display (Figure 12). The 2D application was presented on one of the SAGE2 instances and the 3D application was presented on the other SAGE2 instance. The two participants in front of the large display were asked to interact with one each of the two applications by opening the respective SAGE2 web user application. This separation of applications through two different instances of SAGE2 ensured that the interaction of the participants was limited to one application each. To avoid variability of hardware between the two modes, the participants were presented with the 2D and 3D applications on a high resolution large display in this mode too. To closely mimic a collocated setup where individuals are in the same room but are interacting with their own devices, yet have the ability to look at each others' "screens", I separated the applications by running them on two different SAGE2 instances. In this setup, the VR participant was visually isolated, meaning the VR participant's view of the application was not available to others in the room. This mode served as the control setup against which I compared the integrated setup that is explained below.
- Shared Interaction Mode (SIM): In this mode the high resolution large display had a single instance of SAGE2 controlling the entirety of the display (Figure 13). Both the 2D and the 3D applications were run on the high resolution large display. This allowed the

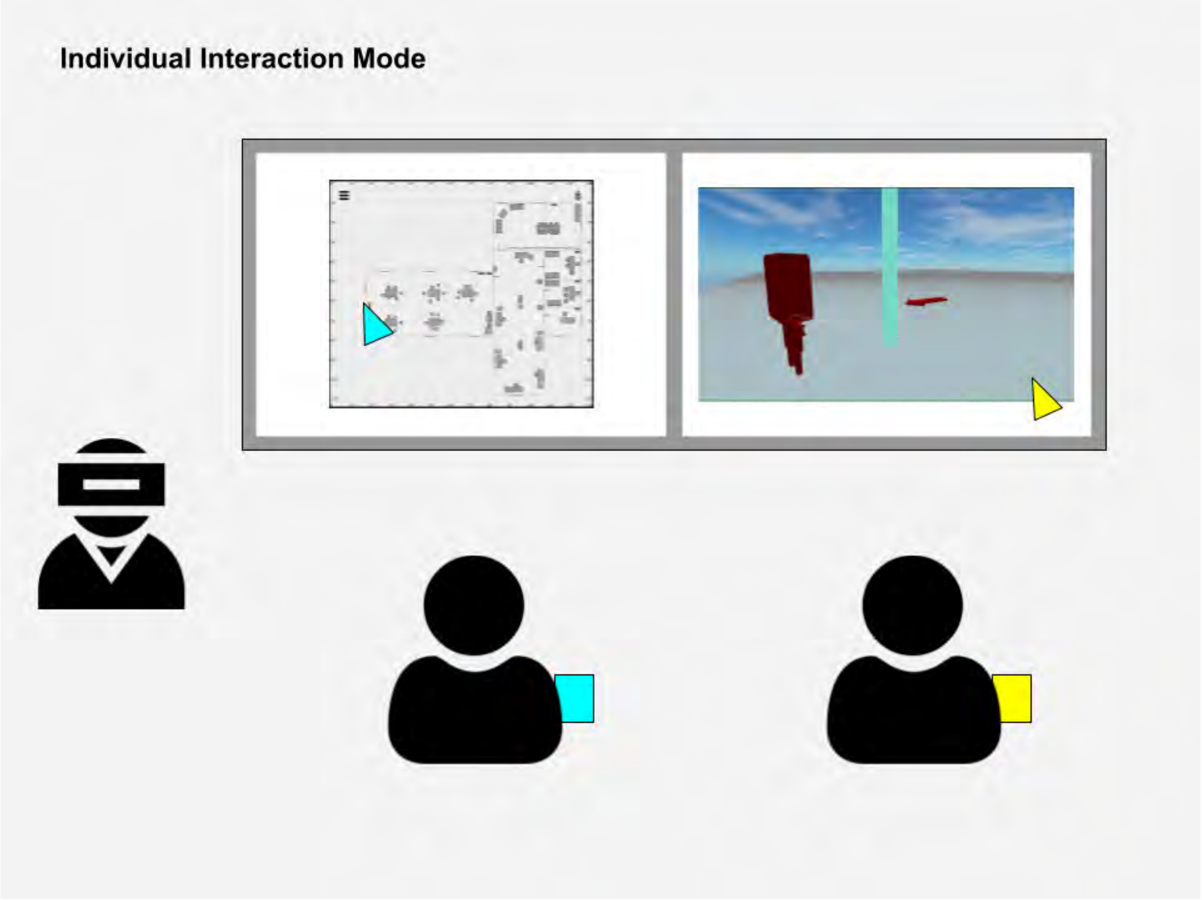


Figure 12: Control Setup

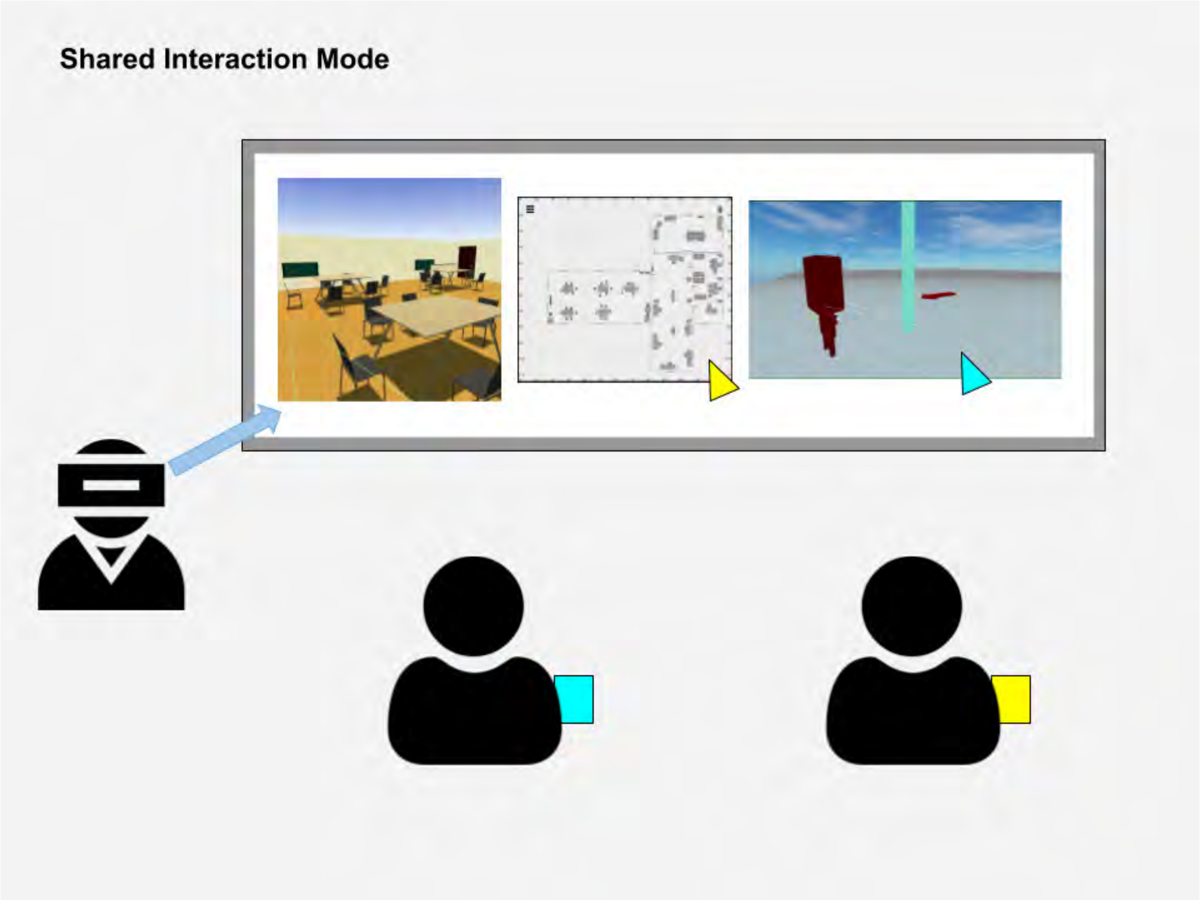


Figure 13: Integrated setup

two participants to freely interact with either of the applications. Additionally, the view of the VR user's application was mirrored on the high resolution large display, allowing the two participants interacting with the high resolution large display to get a passive view of the VR user's perspective of the scene.

TABLE V: Task ordering

Variation	First task	Second task	Third task	Fourth task
1	TaskA - IIM	TaskB - IIM	TaskC - SIM	TaskD - SIM
2	TaskA - SIM	TaskB - SIM	TaskC - IIM	TaskD - IIM

5.2.3 Design

The study had a within group experimental design. Participants from each trial performed collaborative tasks in both the IIM and SIM. Order of performing in the two modes was alternated between trials to avoid any order bias. Each trial consisted of four tasks (two tasks per mode). The participants were given a brief practice session at the beginning of each trial to introduce them to different functionalities of the application they were going to work with and to familiarize them with co-presence, tele-pointing, and communicating with each other.

5.2.3.1 Tasks

The participants were asked to perform two design tasks per condition (see Appendix B for task descriptions), resulting in a total of four design tasks per study session. The same four tasks were given to participants of all the trials. The order of conditions were changed for half the trials to avoid any order bias. That is, for half the trials, variation 1 from the Table V was used and for the other half of the trials variation 2 was be used. The tasks were designed so that they were simple enough to be easily understood and also to be relatable to the participants as they are used to working in labs and offices.

5.2.4 Participants

I recruited participants from among the graduate students from the Departments of Computer Science, Mechanical Engineering, Physics, and Communications at UIC. The participant demographic consisted of 12 men and 3 women, all in the age range of 20 to 35 years. I conducted a total of five trials. None of the participants from the preliminary study were included in this study, hence none of the participants of this study had any prior exposure to this study.

5.2.5 Hardware and Setup

The 2D and 3D applications were presented on a 23.8 foot × 6.7 foot (7.25 m × 2.1 m), 37.3 megapixel large display. The display was situated in a 41 foot × 24 foot (12.5 m × 6.4 m) room. Two participants were seated in front of the large display and interacted with it using laptops. In the same room, the VR application was presented using an HTC vive HMD (display resolution: 1080×1200 per eye (2160×1200 combined pixels), refresh rate: 90 Hz, field of view: 110 degree) to the third participant. The VR user had a 10 × 10 foot (3.05 m × 3.05 m) space to walk around.

5.2.6 Data Collection

During each trial of the user study the participants were audio and video recorded throughout the session. Additionally, the non-HMD participants were asked to wear caps fitted with retro-reflective IR markers to track their gaze direction. The synchronization server of the CVE logs every instruction that is relayed to it by any of the three applications and thus captures every action of each user throughout the session. This log data was also collected for each trial.

The participants were asked to fill out a short written survey and participate in a semi-structured group interview (see Appendix A) at the end of the session. The interview was audio and video recorded. During the group interview, the participants were asked about their experience during the collaborative session including task division, role formation, ease of communication, and any barriers they might have faced in either of the modes.

5.3 Results

All the participants took the tasks seriously and were engaged in the collaborative work during the tasks. Figure 14 shows one of the designs generated at the end of a task in a trial. Henceforth, to anonymize the participants I use the codes 2DP, 3DP, and VRP to refer to the three participants in each trial. 2DP, 3DP, and VRP refer to the participants who were assigned to interact with the 2D application (in the IIM), the 3D application (in the IIM), and the VR application respectively.

I collected both objective data as well as subjective data for analysis purposes. Objective data can be further classified as quantitative and qualitative data. Quantitative data includes system logs, head tracking data, and quantitative measurements of coded data obtained from video recordings such as number of times someone pointed at the screen or number of times the non-HMD users communicated with the VR user and so on. Qualitative data includes conversational fragments that occurred during the trials. Quantitative data will shed light on whether the integration of shared views and shared interactions affected the collaboration and serves as an indicator of whether the integrated setup was useful whereas the qualitative data will give insights into how the shared views and shared interactions affected the collaboration.

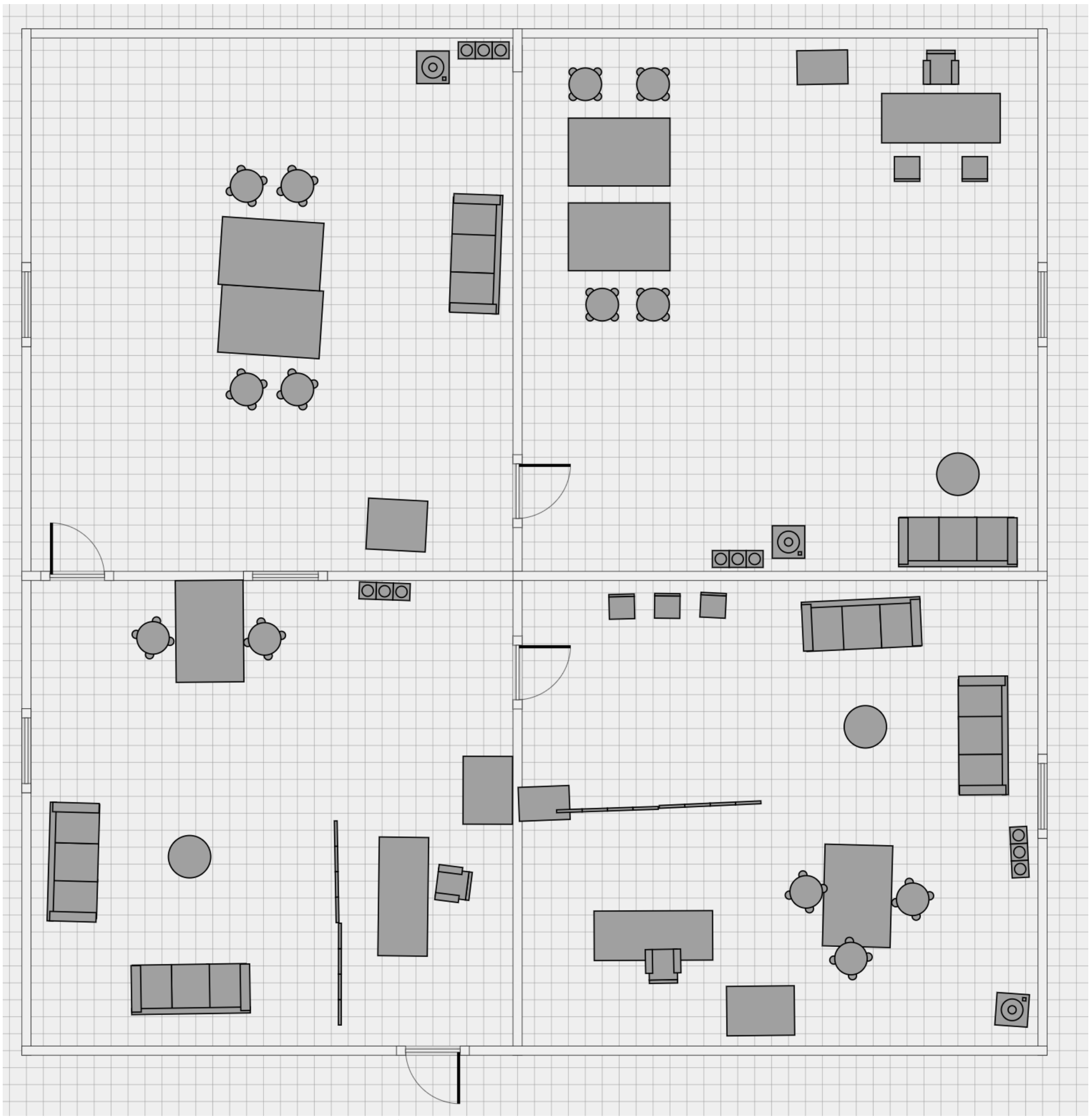


Figure 14: A design generated in one of the tasks

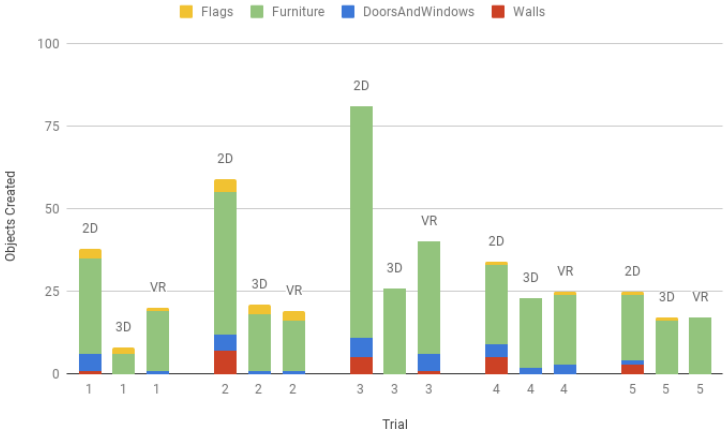


Figure 15: Objects created in IIM

Subjective data includes survey responses and group interviews and was was collected to understand the users' perceptions about the system as well as the integrated setup. This data also serves as a good indicator of attributes such as 'ease' of communication. Now I present the findings from each of these elements of data.

5.3.1 Quantitative Data Analysis

I used the log data from the synchronization server to find out how much each participant interacted with the system. The charts in the Figure 15 and Figure 16 show the number and types of objects created by each participant in IIM and SIM respectively, while Figure 17 and Figure 18 show the number of edits made by the participants in IIM and SIM respectively. Figure 19 shows how much each participant communicated with the others for each task. This data was obtained from video recordings.

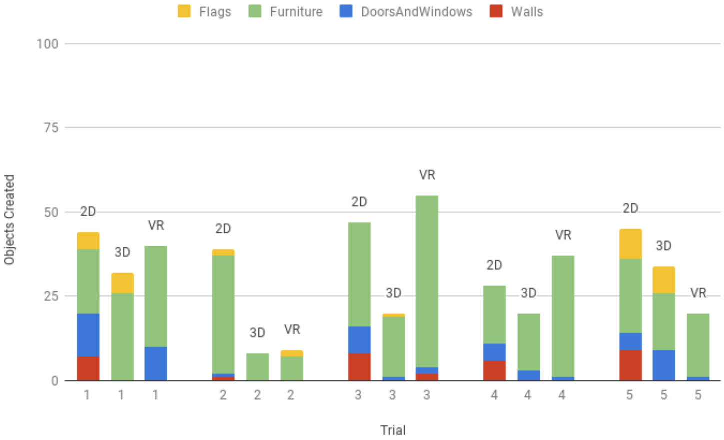


Figure 16: Objects created in SIM

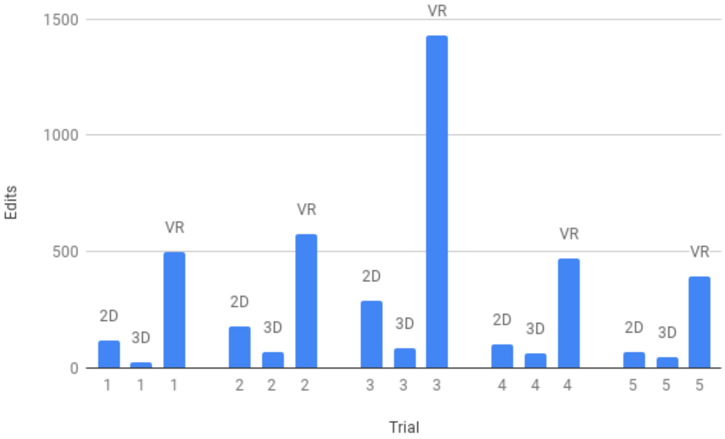


Figure 17: Edits done in IIM

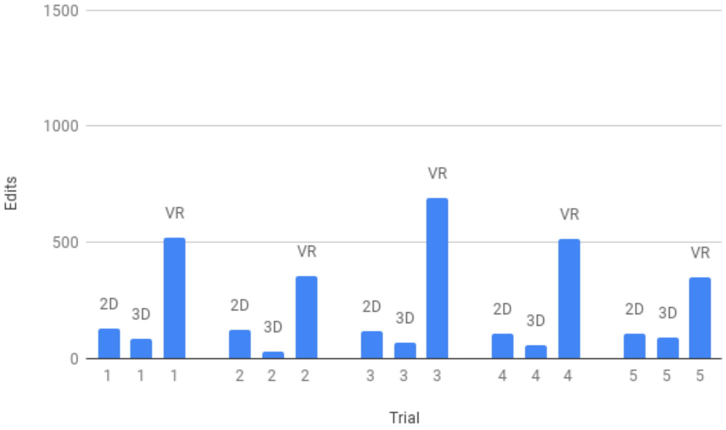


Figure 18: Edits done in SIM

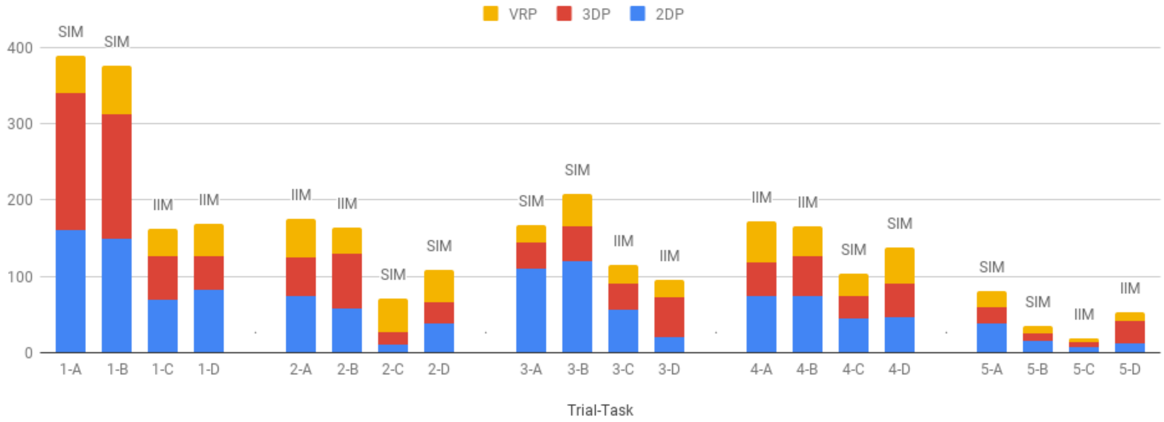


Figure 19: Number of times each participant spoke during the tasks

I used the head tracking data to find out where the non-HMD users were looking at any given point in time. The main areas of interest for this data being the 2D application window, 3D application window and additionally the mirrored view of the VR application during SIM. Figure 20 - Figure 24 show the gaze data for all the five trials. The gaze data clearly shows that the non-HMD participants were looking at both the applications throughout the session. This shows that just having an additional representation was useful. Also, during SIM, the non-HMD participants were looking at the VR mirrored view in short intervals spread across the task duration. This shows that the mirrored view of the VR application was also useful.

Figure 25 shows the number of times, during SIM, the non-HMD participants moved their SAGE2 pointers over to the application that their co-participant was predominantly interacting with. This cross over of pointers indicates that the shared interaction space was useful. Figure 26 shows the number of times, during IIM, the non-HMD participants used their fingers to point to the application their co-participant was interacting with to provide context to their references. Figure 27 shows the number of times different views were used to refer to objects and locations within the scene while communicating with the VR user. Section 5.3.3 further illustrates these results and show how the VR mirrored view was used in the collaboration and how shared interaction was used to ease the collaboration.

Cross over of pointers and pointing gestures are relatively higher for 3DP compared to 2DP. This gap is simply due to the fact that the 2D application presented an overview of the entire scene and thus was more used for referring to objects within the scene as compared to 3D application.

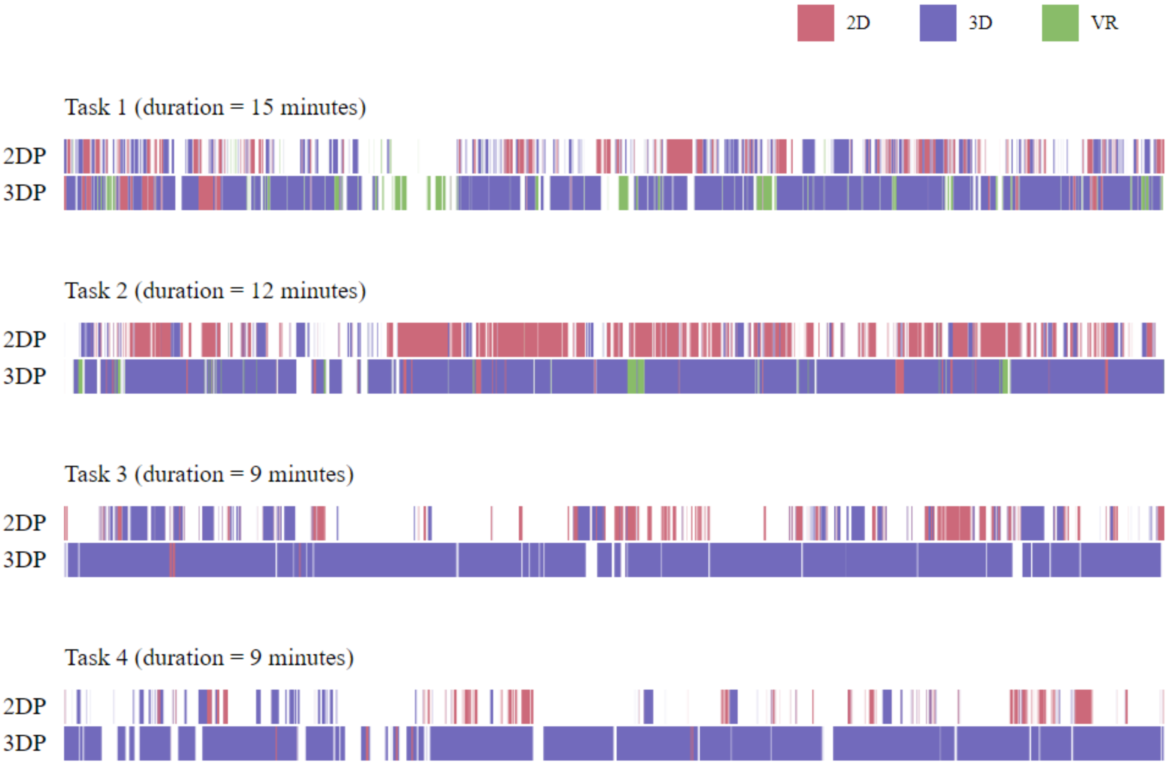


Figure 20: Participants' gaze during trial 1

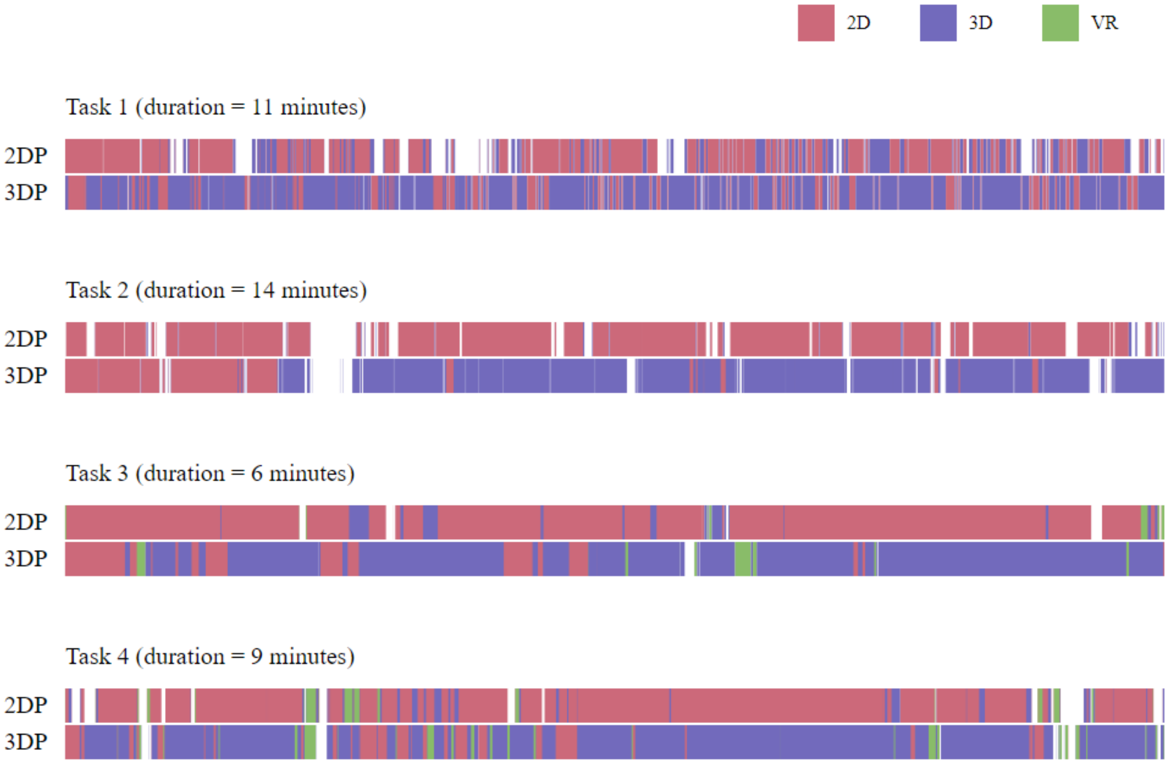


Figure 21: Participants' gaze during trial 2

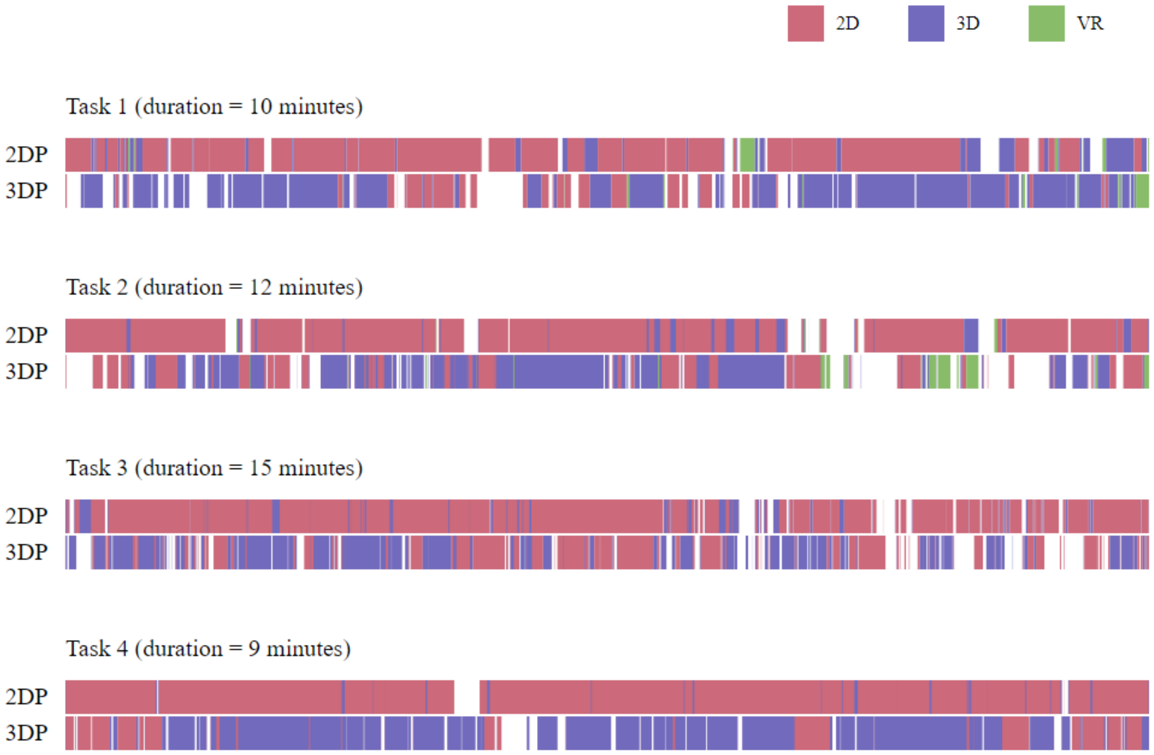


Figure 22: Participants' gaze during trial 3

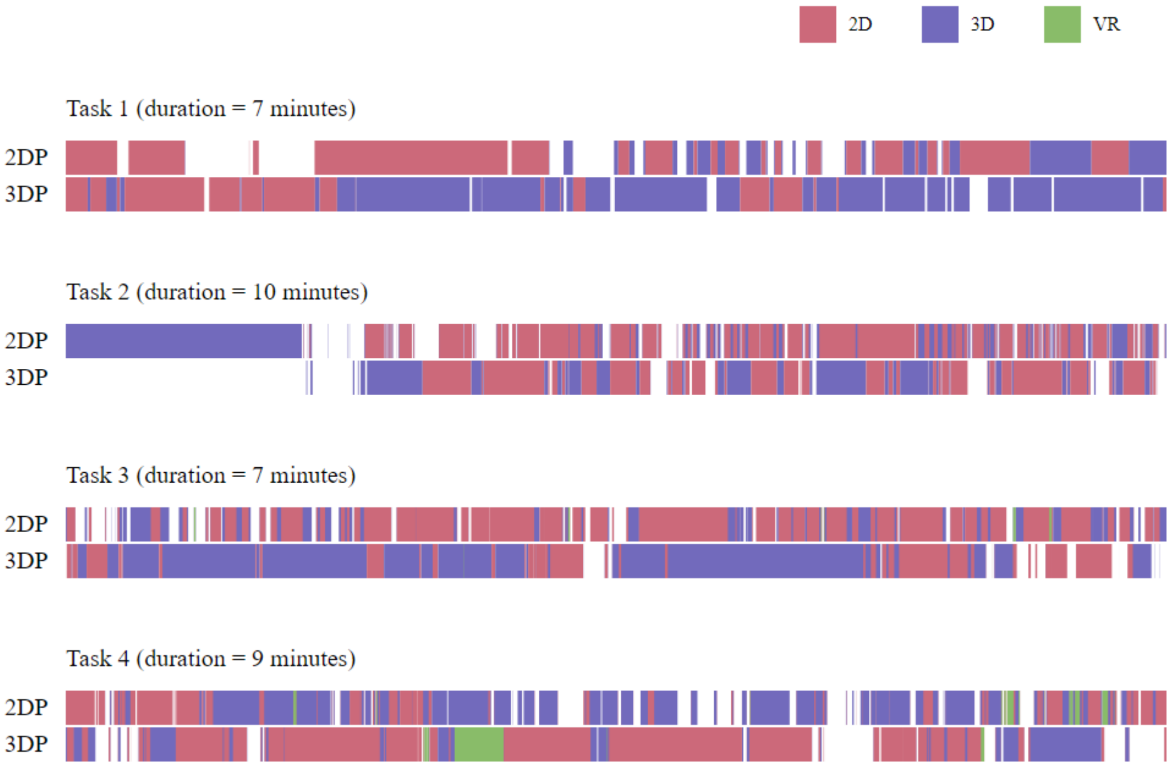


Figure 23: Participants' gaze during trial 4

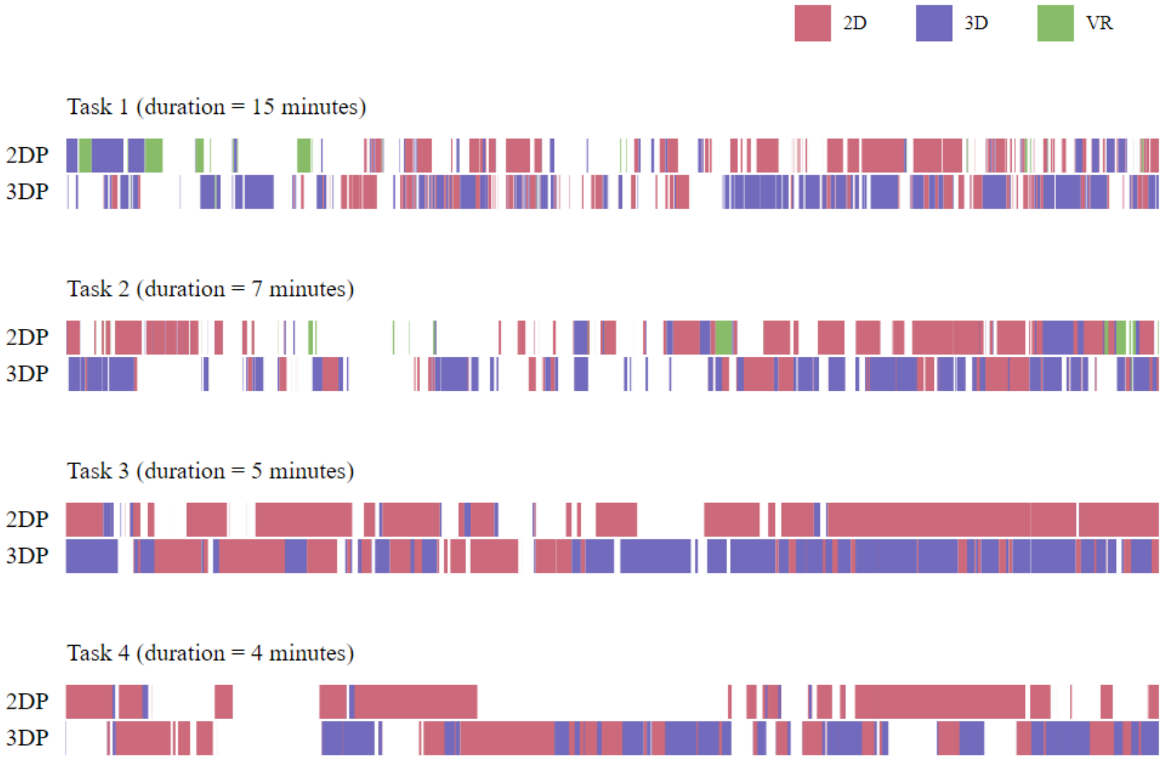


Figure 24: Participants' gaze during trial 5

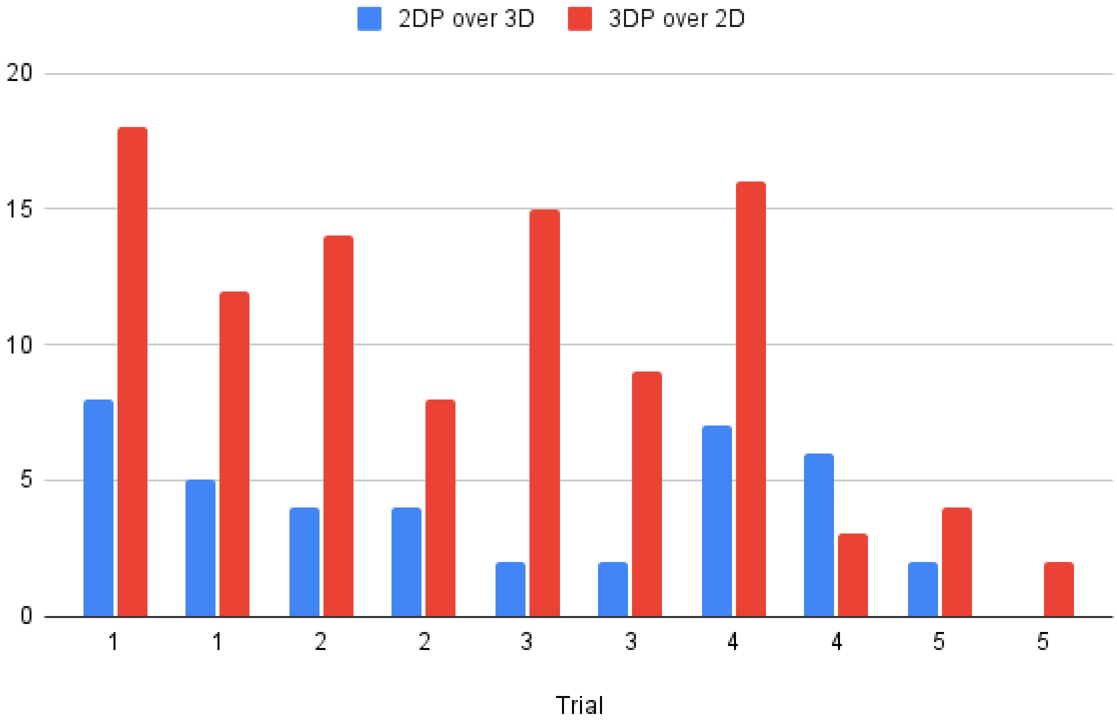


Figure 25: Number of cross interactions of non-HMD users during SIM (using SAGE2 pointers)

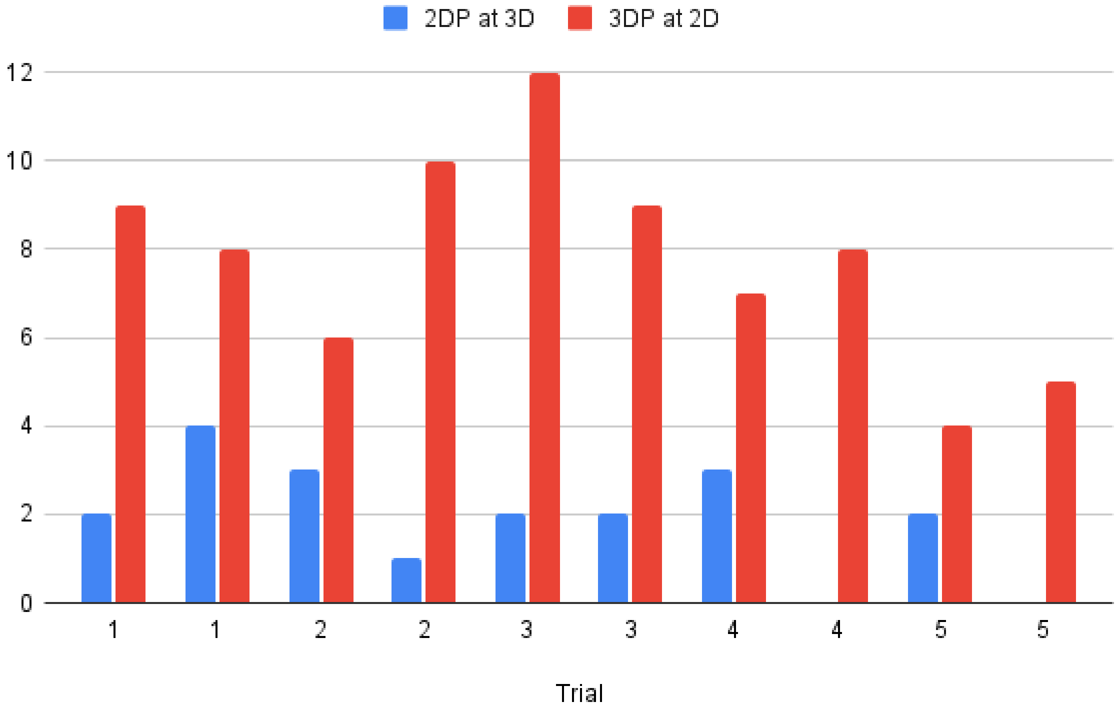


Figure 26: Number of pointing gestures of non-HMD users during IIM

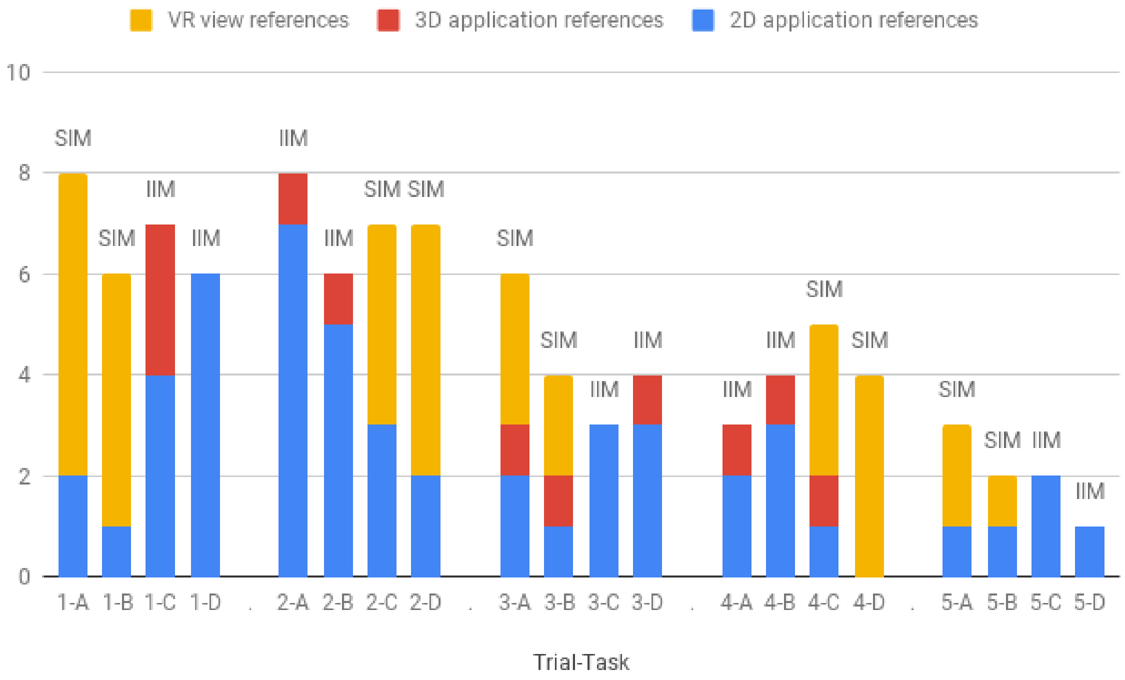


Figure 27: Number of references using different views while communicating with VR user

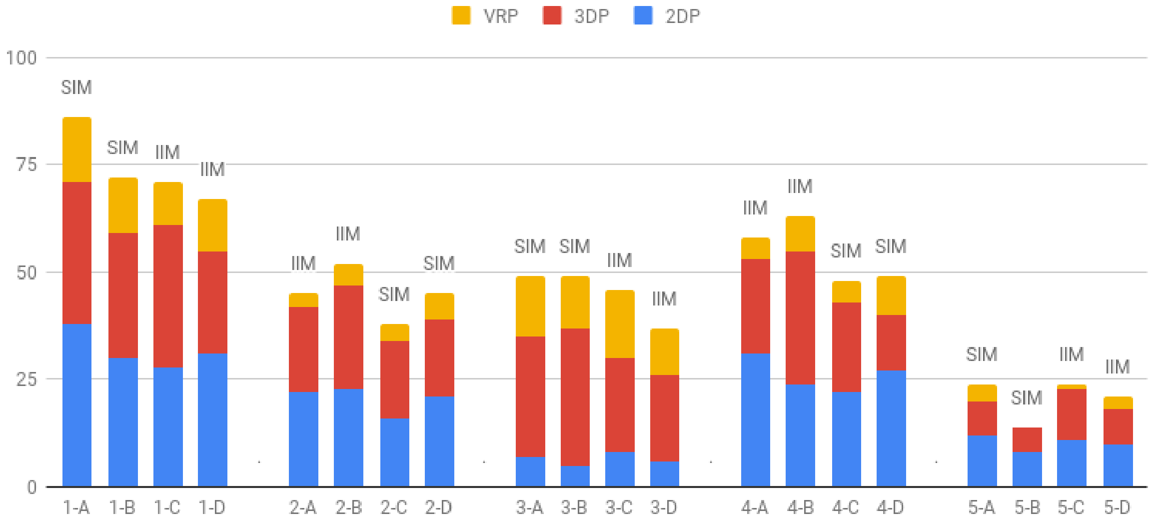


Figure 28: Number of planning and task related directions given

Here I present a few observations that I made analysing the video recordings.

- Similar to the results of the preliminary study, here too it can be noted that certain actions are performed predominantly through one of the applications. For example, Wall creation has been carried out almost exclusively using the 2D application. Most edits have been done through the VR application. This suggests a preference of particular representations for carrying out specific interactions.
- Unlike in the preliminary study where one of the users interacting with the 3D application took on the role of leading the group (giving directions to others on what to do), in these trials the role of leading the group was somewhat less defined. Figure 28 shows the number of planning and task related directions that were given by the participants.

  - In trials 1, 2, and 4, both 2DP and 3DP seemed to share that responsibility. Even during IIM, when they were restricted to interacting with just one application, the shared view of another representation allowed both of them to get involved in planning the next steps and communicating the same with the VR participant.
  - In trials 1 and 3, there were a few instances of even the VRP leading the group in terms of planning the next steps and assigning smaller tasks to the other two members of the group.
  - In trial 3, even though all three participants got involved in the planning phase, it was mostly 3DP that acted as a link between the other two while working on the tasks.
  - In trial 5, participants divided the tasks early on and worked individually with 2DP and 3DP occasionally interacting with each other.

- Interactions between the non-HMD participants and the VR participant during SIM often involved helping the VR participant get the correct reference to what was being discussed whereas during IIM it was mostly about task division at the beginning and catch up and review related communication at the end of the task.

- The VR view references shown in Figure 27 indicate those references that involved demonstrative determiners whereas the rest of the references involved absolute references containing definite noun phrases and references relative to the VR user as perceived in the 2D and 3D applications.

To find out whether the split of interactions among the different applications forced the participants to assume any roles during the collaboration I analyzed the video recordings of all the trials. Here are the findings relevant to the question of representation dependency:

- While in IIM the two participants in front of the large display were limited to interacting with one application each, even in SIM the participants mostly interacted with one application each, the one that was directly in front of them.
- In every trial during SIM, the two participants in front of the large display often, as part of a conversation, moved their SAGE2 pointers over onto the application that their co-participant was predominantly interacting with. This was done to either point at a location within the scene or an object in the scene. For example, to “show” what they thought was a good spot to create the lounge at, or to remove “that” wall, or to rotate “that” table a bit, and so on. Fragment 1 illustrates one such instance. During IIM, to achieve the same effect participants in front of the large display often resorted to pointing with their fingers at the screen or verbally describing other references to drive the point across. Fragment 4 illustrates this.
- In trial 4, during SIM the two participants in front of the large display decided to “switch” the applications they were interacting with, for the entire duration of a task. However, once they switched they mostly kept themselves to interacting with that application. Gaze data of task 4 from trial 4 shown in Figure 23 reflects this cross over.
- In every trial the VR participant would teleport to different parts of the scene including those parts that were being worked upon by the other participants and make finer ad-

justments to the furniture. While the VR application accounts for a lot of edits, the 2D and 3D applications too have their share of edits.

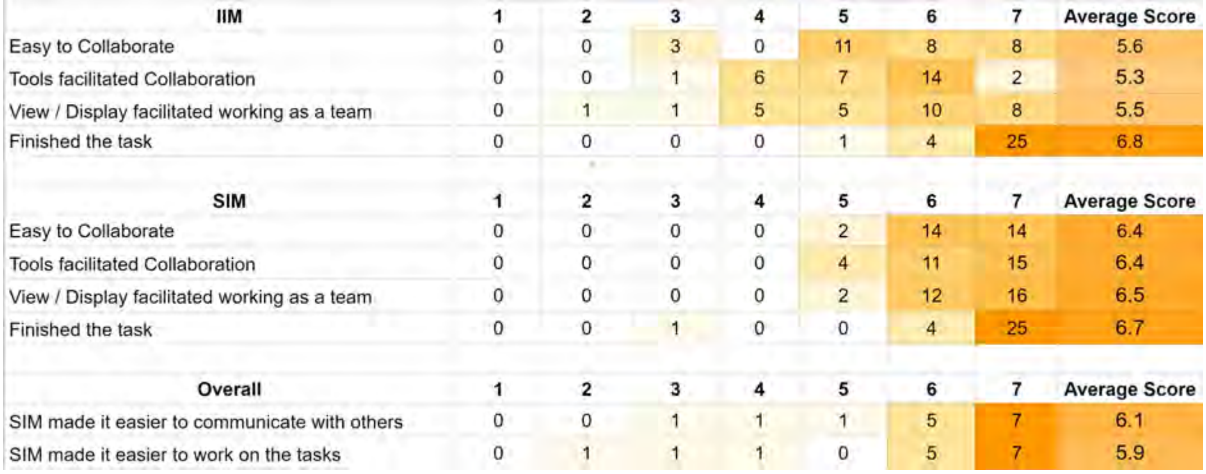
5.3.2 Findings from Subjective Data

User responses help us in understanding the observations made from the quantitative data analyses, hence I present them here before proceeding to qualitative data analysis.

I asked the participants to fill out a brief survey at the end of each task during the user study session. The survey contained a set of questions aimed at getting the participants' opinions on the setup in both the modes with respect to ease of collaboration, ease of communication, and role of large display. Figure 29 shows the number of participants who scored the different questions on a scale of 1 to 7 with 1 being the lowest score and 7 being the highest, along with their average values. The sample size for the task specific questionnaire was 30 (5 trials × 3 participants × 2 tasks) whereas the sample size for the questionnaire comparing the two modes was 15 (5 trials × 3 participants).

Some of the descriptive answers given by the participants explain the relatively small gap between the results of the two modes. During the trials having the participants work in IIM at the beginning, the participants got used to working without the shared interactions and they ended up not utilizing the capabilities of the shared mode to the full extent.

To understand why the two participants interacting with the large display limited themselves to interacting mostly with the application that was directly in front of them, during the group interview at the end of the session I inquired about this behavior. Most of the answers I obtained were different variations of:



IIM	1	2	3	4	5	6	7	Average Score
Easy to Collaborate	0	0	3	0	11	8	8	5.6
Tools facilitated Collaboration	0	0	1	6	7	14	2	5.3
View / Display facilitated working as a team	0	1	1	5	5	10	8	5.5
Finished the task	0	0	0	0	1	4	25	6.8
SIM	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Average Score**
Easy to Collaborate	0	0	0	0	2	14	14	6.4
Tools facilitated Collaboration	0	0	0	0	4	11	15	6.4
View / Display facilitated working as a team	0	0	0	0	2	12	16	6.5
Finished the task	0	0	1	0	0	4	25	6.7
Overall	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Average Score**
SIM made it easier to communicate with others	0	0	1	1	1	5	7	6.1
SIM made it easier to work on the tasks	0	1	1	1	0	5	7	5.9

Figure 29: Survey Results

> “Since he/she was already using that application. I didn’t feel the need to. If I wanted something to be done using the application that my co-participant was interacting with, I could always ask them to do it.”

A few of the participants from trials that had IIM at the beginning of the session responded with:

> “By the end of the second task, we were used to interacting with one of the applications and just didn’t feel like changing that at that point.”

Here I present a summary of responses from the group interviews that are relevant to my research questions:

- Upon being asked in which mode they felt like they accomplished more, 6 of the 15 participants responded by saying they felt they accomplished more in SIM whereas the rest of them did not find any difference in how they fared in both the modes.
- 9 of the 15 participants felt that it was easier to perform the tasks in SIM. 3 out of the remaining 6 did not find any difference between the two modes with respect to ease of performing the tasks. These 3 participants were assigned to the VR application. 3 non-HMD participants felt that it was easier to perform the tasks in IIM. When asked why they felt so, they responded that they felt like they were being interrupted when their co-participants tried using the application they were interacting with in SIM and that they liked how in IIM they were able to work without any such interruptions.
- 2 of the 15 participants felt that they wasted their efforts while performing the tasks, however this was a reflection on some of the glitches they encountered in the software during the trials rather than being related to the affordances or limitations of either of the modes.
- 12 of the 15 participants (including 3 participants who interacted with the VR application) felt that communication with their co-participants was better in SIM. The remaining 3 participants did not find any differences in how the group communicated between the two modes.
- Only 3 of the 15 participants felt that they worked less compared to their co-participants. However their response was more generally about the whole session rather than being about either of the two modes. Also, almost all of them thought of work as only consisting

of their interactions with the applications and did not take into account any interactions they had with each other.

5.3.3 Qualitative Data Analysis: Conversational fragments

In this section, I present the analysis (Mazeland, 2006) of a few conversational fragments that occurred during the user study trials. These fragments are representative of some commonly occurring scenarios throughout the study. They provide insights into how the SIM compares with IIM with respect to the different research questions I investigated. The convention followed in the fragments is as follows:

- Each speaker's turn is on a separate line.

(0.4) A decimal number between parentheses denotes the length of silence between or within turns, measured in tenths of a second.

(.) Dot between parentheses denotes a short silence (less than 0.2 seconds).

[In case of simultaneous talk, the onset of the overlapping turn is denoted by a left square bracket in the current turn.

wor:d A colon denotes a noticeable sound stretch.

. A period indicates a falling pitch contour.

, A comma indicates a slightly rising pitch contour.

? A question mark indicates a strongly rising pitch contour.

5.3.3.1 Fragment 1

3DP: this whole part?
2DP: yeah?
3DP: we could have like a receptionist
2DP: oh, at one corner over here?
3DP: yea:h. And then [like
2DP: and a lounge area over there?
3DP: yeah, yeah, so (0.4) the receptionist is her:e and then the door to
the main office is her:e and [then,
2DP: yeah. ok that would work

In this fragment the participants have just begun to work on the first task (in the SIM) and are in the planning phase. Moments before this fragment 2DP volunteers to divide the space into two rooms by creating a wall. 3DP asks 2DP if he means to partition the entire right portion of the space by moving his SAGE2 pointer on the 2D application to trace a rectangular area over it. 2DP confirms that. 3DP then makes a suggestion of having a receptionist's area in that room. 2DP asks if that should be in a corner of that partition, moving his SAGE2 pointer to a point within the area they are talking about. 3DP agrees and 2DP interrupts him and asks whether they should also have a lounge area at the other end of the space by moving his SAGE2 pointer to that location on the 2D application. 3DP agrees and summarizes by showing 2DP where the receptionist should be by moving his SAGE2 pointer to that location on the 2D application and then shows where the door leading to the main office should be placed by wiggling his SAGE2 pointer at a location along a line where they decided to build the partitioning wall. This fragment illustrates how the SIM seems to enable the participants to make use of demonstrative determiners like “here”, “there”, “this”, and “that” to refer to objects and locations in the scene with SAGE2 pointers being used to provide the necessary context for the references.

5.3.3.2 Fragment 2

VRP: hey gu:ys. (0.5) can you tell me the dimensions of this room?
2DP: this is (0.7) 40 feet I thin:k and (0.6) this is 15 feet
3DP: yeah (0.4) so where you are facing right now? (0.3) that is 15 feet
2DP: yeah (.) so the short side is 15 and long side is 40

This fragment takes place later in the same trial as fragment 1. 2DP has partitioned the space into two rooms and VRP has just stepped into the room 2DP and 3DP were planning in fragment 1. VRP looks around the room and asks for the dimensions of the room. His view is visible to 2DP and 3DP as they are working in the SIM. 2DP runs his SAGE2 pointer along the length of the longer wall of the room on the 2D application and uses the grid to determine its length and announces it to be 40 feet and repeats the process with an adjoining wall and announces it to be 15 feet. However, since VRP cannot see which walls were being referred to, 3DP turns to look at the VRP’s mirrored view and notices VRP to be facing the longer wall of the room. So he uses VRP’s view as reference to tell him that the distance between him and the wall he is facing is 15 feet. 2DP supplements this information by saying the longer of the two sides is 40 feet. The SIM seems to facilitate the non-HMD participants to use VRP’s view to make references to objects in VRP’s view thereby allowing VRP to easily make sense of those references.

5.3.3.3 Fragment 3

VRP: ok (.) i think (.) one of the offices is done. is this fine or do
you [guys want anything else? in here
2DP: yeah ok (0.4) what is (0.3) hold that pose (0.4) what are you
seeing right now? (0.7)
2DP: yea:h yea:h lower (0.3) lower (0.4) is that? (0.4) oh.
its a drawer. ok ok.

This fragment takes place when the participants are in the middle of task 2 in which they are supposed to create three individual rooms as part of the task requirements. During the planning phase at the beginning of the task, VRP suggests that he will furnish one of the rooms. 2DP agrees and suggests that once VRP is done furnishing the room, 2DP can replicate that in the other rooms to make them appear uniform. His co-participants like this idea and agree to it. This fragment takes place when VRP finishes furnishing the room and announces it to the others. 2DP is looking at the 2D application when he hears VRP make the announcement. He notices the direction VRP is oriented at that moment through the human icon representation of VRP in the 2D application and asks him what it is that VRP is seeing directly in front of him. He wants to replicate it in the other rooms but he seems to not be able to distinguish what it is from just the top view as seen in the 2D application. He also seems to have forgotten about VRP's mirrored view being available. 3DP seems to notice this and points to VRP's view using his hand. 2DP looks at VRP's view and notices VRP's gaze is directed upwards and hence the object of his inquiry is not in view. He says "lower, lower". VRP understands that 2DP is talking to him and lowers his gaze to reveal a drawer in front of him. This fragment is an example of collaborative exchanges where the mirrored view of VRP is used to disambiguate and identify objects placed in the scene. Of course, the same effect could have been achieved by using the 3D application (or asking the 3DP to use the 3D application) to navigate to the location under inquiry and seeing through the 3D application. However, due to proximity of the VR user to the object and the readily available VR view seems to appeal to the non-HMD participants as the easiest way of achieving the goal.

5.3.3.4 Fragment 4

2DP: so what about like (.) the middle of the room (0.3) do you
want to make use of the empty space there?
VRP: um:m (0.4) in the middle may be. (0.5) we can place
one (.) or two tables?
3DP: yeah so like (0.3) so can you put your desks where you said?
2DP: you mean earlier?
3DP: yeah. your first idea

This fragment takes place just as the participants begin task 3. They are discussing how the layout of the room should be when VRP suggests that they should make the layout such that every student would be facing the walls and that would ensure that every student would have easy access to any of the exits. 2DP asks if they should make use of the space in the middle of the room. VRP responds by saying they can have one or two tables in the middle. 3DP seems to have an alternative idea that's based on a prior discussion that ensued moments before this fragment when 2DP had suggested putting a couple of tables next to one of the doors. In order to explain his alternative idea 3DP begins by trying to move his SAGE2 pointer across the display onto the 2D application only to notice he cannot move his pointer onto the 2D application since they are in the IIM. He then asks 2DP to put the desks where he had put them earlier, and then proceeds to explain his alternative idea from there. Here 3DP resorts to using references from his memory to convey to his co-participant an idea that he initially tries to convey by showing it himself on the 2D application. Several such indirect and alternative references occur in every trial during the IIM.

5.3.3.5 Fragment 5

VRP: can you align that chair over there?
2DP: sorry (.) which chair?
VRP: that one.
2DP: i can't see what you are seeing.
VRP: this chair (0.3) i'm moving it
2DP: oh, i see.

This fragment comes about in the middle of task 1 (in IIM). This group divided the work so that 2DP and 3DP would work on setting up the office while VRP worked on the lounge. In this fragment, 2DP and 3DP have just finished furnishing the office. VRP is still working on the lounge area. When they notice that VRP is still working, 2DP and 3DP offer to assist him. VRP agrees and asks them to align a chair (this particular user was finding it difficult to make finer rotations to objects using the VR controller) 2DP asks which chair he is referring to. At this, VRP points the VR wand ray at the chair and says "that one" without realizing they cannot see where he is pointing. 2DP reminds him. VRP then grabs the chair in question and moves it back and forth and indicates to 2DP that he is referring to that chair. In the absence of a shared view, VRP is forced to refer to objects and positions using extraneous interactions that don't seem to be relevant to the task at hand.

5.3.3.6 Fragment 6

2DP: where do you want me to put this desk?
VRP: over here
3DP: use a marker
VRP: uh: (0.6) here
2DP: ok

This fragment occurs later in the same task as that of fragment 5. 2DP and 3DP are assisting VRP in furnishing the lounge area. 2DP creates a desk and asks VRP where to place it. VRP, again forgetting that they can't see what he sees, points to a location and says "over here". 3DP suggests he use a marker(flag). VRP creates a flag from the menu and places it at the spot he was referring to earlier and says "here". 2DP moves the table to the location of the flag. Shared view allows the VRP to engage more demonstrative determiners and in the absence of it, VRP is forced to rely on alternatives to communicate with non-HMD participants.

5.3.4 Mapping the results to the research questions

In this section I map the results to the research questions I formulated.

1. Mitigation of effects of dependency on representations.
2. Improved transparency of the collaborative setup.
3. Ease of communication between group members.
4. Improved work share.

5.3.4.1 Mitigation of role formation due to representation dependency

The fact that the participants moved their SAGE2 pointers onto the “other” application whenever they wanted shows that they were free to interact with either of the applications in SIM and the participants were aware of this. Their responses on the matter during the group interview suggests that their behavior was driven by social etiquette more than anything and for a few of them it was more about being used to interacting a certain way. This shows that any roles that were formed during the collaboration were not forced upon the participants by the applications (representations).

5.3.4.2 Improved transparency of the collaborative setup

Group interview responses (Section 5.3.2) for task accomplishment and ease of performing tasks fail to clearly show how SIM affected the transparency of the system. However, when we compare fragments 1, 2, and 3, with fragments 5 and 6, it becomes evident that SIM improves the transparency of the system by cutting down a lot of extraneous interactions that the participants are forced to resort to simply to provide context for their references in the absence of a shared VR view and shared interactions.

5.3.4.3 Ease of communication between group members

Group interview responses on ease of communication suggest that SIM did improve ease of communication between participants. Fragments 1 and 2 further shed light on how SIM improved communication between the participants by allowing them to make use of demonstrative determiners instead of uniquely identifiable references or definite noun phrases that require more effort on the part of the speaker to be able to generate them when referring to objects or

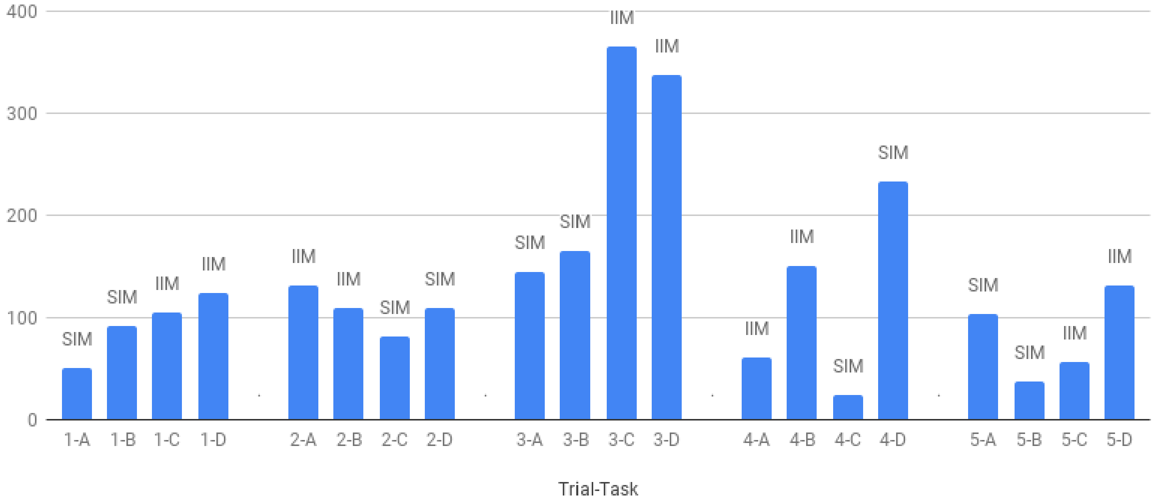


Figure 30: Standard Deviation of in-group work share for all tasks

places. More so, when the scene is crowded with many objects (or the area is large and complex in case of positional references).

5.3.4.4 Improved work share

Group interview responses fail to indicate how SIM affected work share. However, through the logs and video recording I was able to compute the total interaction units of each participant considering each individual interaction (an object created, a task related instruction given, and so on. Figure 15 - Figure 19) from any of the different phases of collaboration as a unit of interaction for both of the modes. The results are shown in Table VI

Standard Deviation (SD) is a measure of how spread the data elements are, around the mean. Larger the SD, larger the spread. With respect to work share values within a group, larger SD values implies a greater imbalance in the work share between group members and

TABLE VI: Comparison of workshare in IIM and SIM

Trial	Task	Mode	2D Work	3D Work	VR Work	Mean	Variance	SD
1	A	SIM	206	215	300	240	2690	51
1	B	SIM	234	213	382	276	8484	92
1	C	IIM	122	74	276	157	11137	105
1	D	IIM	146	53	300	166	15562	124
2	A	IIM	153	89	344	195	17600	132
2	B	IIM	158	100	314	190	12249	110
2	C	SIM	51	28	181	86	6806	82
2	D	SIM	122	44	261	142	12082	109
3	A	SIM	144	77	355	192	21049	145
3	B	SIM	204	70	400	224	27545	165
3	C	IIM	217	81	771	356	133585	365
3	D	IIM	149	91	703	314	114137	337
4	A	IIM	114	78	197	129	3724	61
4	B	IIM	136	82	367	195	22917	151
4	C	SIM	93	56	101	83	576	24
4	D	SIM	102	77	491	223	53890	232
5	A	SIM	101	58	255	138	10729	103
5	B	SIM	59	63	125	82	1369	37
5	C	IIM	23	26	123	57	3236	56
5	D	IIM	63	55	288	135	17496	132

a close to zero SD would mean that all members of the group worked equally. Hence SD is a good indicator of work share balance within the group. For easy comparison of SDs of all the tasks, I have presented those values in Figure 30. As can be seen, SIM does show a smaller SD in most of the cases indicating a smaller spread of the work share between the group members suggesting an improved work share.

5.4 Discussion

Here I present some of the assumptions my research work is based upon and some limitations specific to the system and generally applicable to the shared interaction space and discuss the applicability of this work. The hybrid collaborative virtual environment prototype that I created is representative of a cooperation level 2 system and thus assumes that the users will at most create and interact with different objects simultaneously and will not try to cooperate on a single object at any given point. The different representations, although created to support interdisciplinary collaboration, remain fairly generic in terms of the functionality they afford and thus allow any user to move between them. Incorporating niche representations that are designed for specific groups of domain experts might make it less easy for users to move between different representations and might warrant a rigorous training of the users with the system before they reach the same level of ease in interacting with all the different representations. Furthermore, in such a case, the group dynamics is likely to change and further research is needed to assess that. The different representations all offer the same set of functionalities with respect to what a user can do within the virtual environment and this serves as the single most important reason for why users feel free to move between different representations based on their perceptions of what actions are easier on each representation. The observations made during the preliminary study as well as the formal study are all predicated upon this aspect of the collaborative setup.

The collaborative setup assumes that the users have a basic level of understanding of generic software tools such as web browsers and web applications and some familiarity with hardware tools like virtual reality headsets and large displays. The problem of architectural design is generic enough such that it is reasonable to assume that any user would be familiar with the general details that go with the problem statement as well as what is expected of a user trying to solve the problem. The tasks of both the studies were kept open ended to encourage discussion and planning as part of the collaboration. The group dynamics as well as emergence of different roles are likely to be affected if the tasks were to be more restricted.

Even though the hybrid collaborative environment prototype that I created makes use of three representations, namely 2D, 3D, and VR, the observations made and the lessons learned during the studies are not limited to this setup and extend suitably to any combination of different representations as long as the aforementioned completeness of the individual representations is ensured.

Integration of shared views and shared interactions enable the users to work with a common frame of reference even in the physical space and this common frame of reference is what helps in reducing extraneous interactions and eases communication between the users. This is the key take away from this research effort. Any collaborative system looking to improve communication between its users should look for ways to provide its users with a common frame of reference and a means to provide context to their references.

Findings from both the preliminary study as well as the formal study concur with the lessons I learned (Section 2.7) from other systems that are relevant to my work. These findings are all generic enough that they can be applied to not just such hybrid virtual environments but to any collaborative environment that has different users interacting with different ”windows”, even to systems that address problems that do not have a fixed goal like designing/building something but are just about letting people come together to solve a problem. The challenges of asynchronous collaboration are significantly different from that of synchronous collaboration and hence further research is needed to see if these findings extend to asynchronous systems as well. These findings are based on studies conducted on small groups (group size ¡ 10) and apply to groups of similar sizes. Based on these findings I feel that the four categories of collaborative systems that we saw in Chapter 2 can be improved as follows:

- Systems with uniform hardware and uniform views: Providing the users a point of view that is common to all users along with their own points of view and the ability to either put these two views side by side or toggle between them could help the users establish a common reference of the data and thus improve the collaboration. This common point of view need not be an overview of the entire scene/data, just a view that is exactly the same for each user of the system. A real world example of such a common point of view would be the speaker view in the Zoom video conferencing software. Individual users all see the same view, that is whoever is speaking at the time, but have the ability to see a specific user's video. Taking the Zoom analogy, it would be like flipping it around to let each user by default have their own view but have the option to see this common view at any point.

- Systems with different hardware and uniform views: Due to differences in hardware it might not be possible to provide a common point of view for all users for this class of systems. Since there already exists some notion of uniformity among the views presented of different hardware, providing the users with the ability to replicate each other's views even if only as an overview could be an alternative to achieve a common reference point at least among subsets of users within the larger group.
- Systems with uniform hardware and different views: Ensuring that the different views are not split between the different devices but are all available to every user and providing easy means to mirror each other's views would enable users to "be on the same page" on demand.
- Systems with different hardware and different views: Apart from making different views available on each device similar to the previous category, these systems must provide a way to translate between the interaction metaphors of different devices so that it is easy to share interactions between them.

CHAPTER 6

CONCLUSION

In this dissertation I have provided a solution for supporting interdisciplinary collaboration in the form of a hybrid collaborative virtual environment. I conducted a preliminary user study of the hybrid collaborative virtual environment to evaluate the general usability of the system and the results of the study showed that the users found it fairly easy to work with the system. The preliminary study also revealed that when users are limited to working with one application or representation, it can lead to some of the users being forced to assume certain roles during the collaborative session.

Based on existing research on large displays, I believe that they can be effectively employed in the collaborative setup to integrate shared views and shared interactions into the collaborative setup to address the representation dependency issue. Thus I formulated the following research questions.

1. **How will the integration of shared views and shared interactions with the hybrid CVE affect group collaboration in such a hybrid CVE? Specifically, how will the integration affect the formation of spontaneous roles that are influenced by dependency on representations in such a hybrid CVE?**
2. **Will the integration improve the transparency of the collaborative environment?**

3. **Will the integration make it easier for the group members to communicate with each other?**
4. **Will the integration improve the work share between the group members?**

I conducted a formal user study to answer my research questions. The study results suggest that the integration does indeed mitigate the role formation due to representational dependency and has some merits with respect to improving the transparency of the system, improving the communication between the group members, and improving the workshare between them. The study also revealed a few instances where the participants were less inclined to work in the integrated setup. That is, a few participants felt like they were being interrupted when their co-participants tried to interact with a shared application that they were interacting with, despite the application supporting multi-user interactions. In conclusion, the integration of a high resolution large shared display with the hybrid collaborative environment improved the overall collaborative experience.

6.1 Future research directions

Multiple instances of each application on the large display: Even when an application supports multi-user interactions, some negotiation might become necessary in order to properly utilize such capabilities. Negotiation during group collaboration for a shared resource or in this case a shared application, is very much dependent on the interpersonal communication skills of the group members. Hence there will always be some groups for which such negotiation will not be a problem and some groups for which it might seem like a hurdle. To accommodate the needs of such diverse groups, we could further exploit the screen real estate of the high resolution large shared display to provide multiple instances of each of the applications in the hybrid setup on the large display. This increases the number of the applications that are readily available for an individual in the group to interact with, decreasing the need to negotiate for control over a shared application.

Two way sharing of views and interactions with the VR user: Even though the non-HMD participants often used the mirrored view of the VR application to provide positional references to the VR participants to help them easily identify and locate the objects or locations being discussed, the ability to simply use demonstrative determiners and "point" to objects could further improve the communication between VR participants and their co-participants. Replicating the SAGE2 pointer positions, within the VR application, as they move on the mirrored view of the VR participant could make this "pointing and showing" possible.

Further, the VR application could be enhanced by providing a 2D overview map of the scene that could be toggled on and off by the VR participant as needed. Whenever the VR participant points at the overview map, appropriate markers could be shown on the 2D and 3D applications to enable the VR user to also "point and show".

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APPENDICES

Appendix A

SEMI-STRUCTURED INTERVIEW

Guiding questions: [Evaluation lines of inquiry that a question addresses, have been denoted next to the questions wherever applicable]

1. In which one of the two modes do you feel you accomplished more? (Different people define “accomplish” differently, so exploration of this question will focus on that definition and how the two modes compare with respect to that) [2.a]
   (a) Why do you feel so?
2. In which one of the two modes was it easier to perform the tasks? [2.a]
   (a) What aspects about that mode made it easier?
3. How did you divide the work? (Reviewing of work should also be covered under this question, to see whether reviewing specifically was divided or if just one person took that responsibility.) [1, 2.c]
   (a) Why did you decide to divide the work that way?
   (b) (From observation determine whether any simultaneous roles occurred during the session) I noticed that you assumed different roles such as (describe the roles that were observed). What influenced your decisions there?
   (c) Between the two modes, were there any differences in how you divided the work?

Appendix A (Continued)

   (d) (address to each individual in the group separately) Do you feel you worked more than the rest of the group or less than the rest of the group?
      i. (If yes) Please elaborate on what you did and explain why you feel that it was more (or less) compared to the rest of the group.

4. In which one of the two modes was it easier to coordinate with each other over the smaller sub tasks? [2.c]
   (a) What aspects of the setup in that mode made it easier to coordinate?
5. Were you able to clearly communicate your thoughts and ideas with each other throughout the session? [2.b]
   (a) What improvements can we make to the setup to facilitate better communication?
6. Were there any instances during the session when you felt your efforts were being wasted, or you had to put in extra efforts on the account of the setup not supporting what you wanted to do? [1, 2.a]
7. In which one of the two modes do you feel the end result (the design) of your work was better?
8. Do you have any suggestions for improving the setup so that it can better facilitate group collaboration?

Appendix B

TASKS FOR THE USER STUDY

Task A

In the area provided, create an office space with:

- Main office: Should accommodate one employee and three visitors
- Lounge area: Should be able to accommodate a receptionist and four visitors who are waiting.

Task B

Given office space holds two 15' by 30' office rooms and an open office area. Remodel the given office space to hold three 20' by 20' office rooms and furnish the rooms suitably. Also furnish the open area to accommodate four employees.

Task C

Given space is intended to be a work area for PhD students at a lab. With new incoming PhD students, your task is to optimize the space to accommodate as many students (each student will need a desk and a chair) as possible. Please make sure that every student can walk to any of the exits with nothing blocking their way.

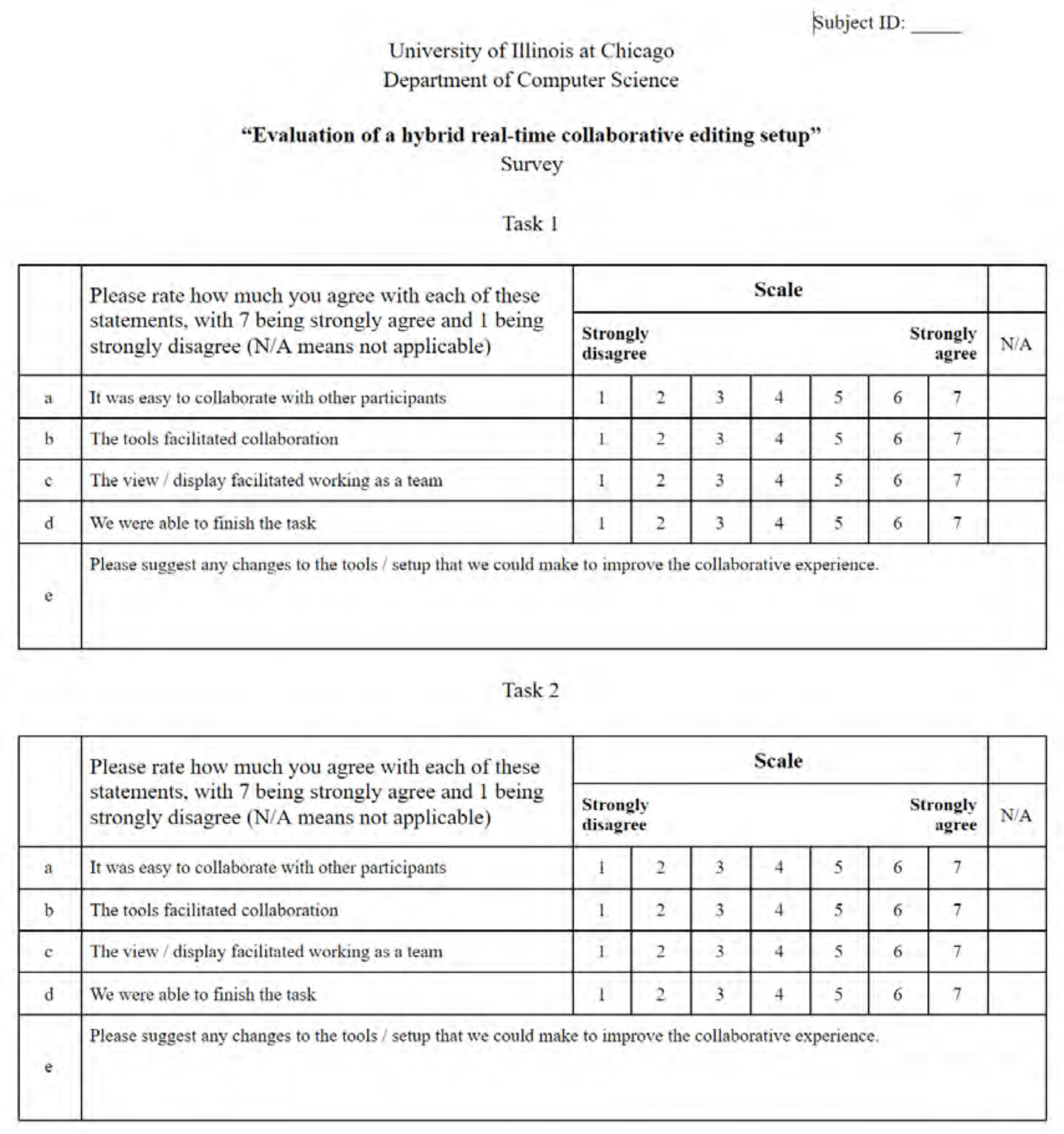
Task D

In the given space, create a conference room with an adjoining break room.

Appendix C

WRITTEN SURVEY

Appendix C (Continued)



Subject ID: _____

University of Illinois at Chicago
Department of Computer Science

"Evaluation of a hybrid real-time collaborative editing setup"
Survey

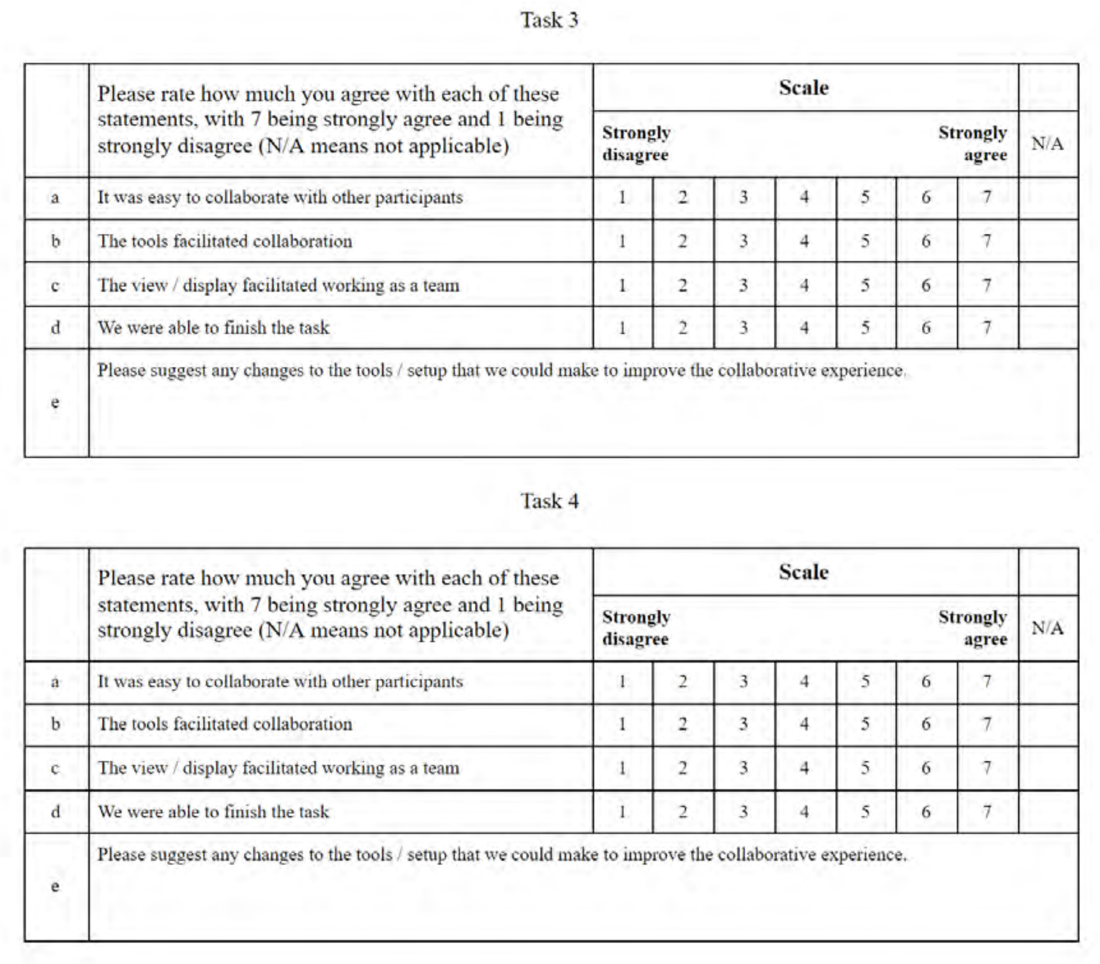
Task 1

	Please rate how much you agree with each of these statements, with 7 being strongly agree and 1 being strongly disagree (N/A means not applicable)	**Scale**							
		Strongly disagree						**Strongly agree**	N/A
a	It was easy to collaborate with other participants	1	2	3	4	5	6	7	
b	The tools facilitated collaboration	1	2	3	4	5	6	7	
c	The view / display facilitated working as a team	1	2	3	4	5	6	7	
d	We were able to finish the task	1	2	3	4	5	6	7	
e	Please suggest any changes to the tools / setup that we could make to improve the collaborative experience.								

Task 2

	Please rate how much you agree with each of these statements, with 7 being strongly agree and 1 being strongly disagree (N/A means not applicable)	**Scale**							
		Strongly disagree						**Strongly agree**	N/A
a	It was easy to collaborate with other participants	1	2	3	4	5	6	7	
b	The tools facilitated collaboration	1	2	3	4	5	6	7	
c	The view / display facilitated working as a team	1	2	3	4	5	6	7	
d	We were able to finish the task	1	2	3	4	5	6	7	
e	Please suggest any changes to the tools / setup that we could make to improve the collaborative experience.								

Appendix C (Continued)



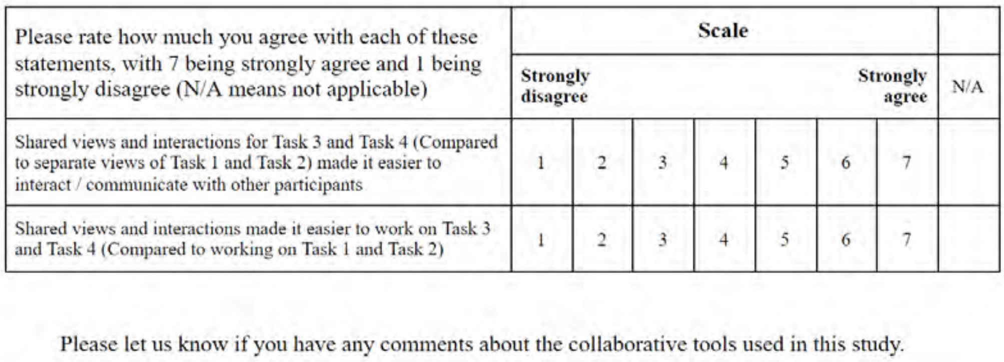
Task 3

	Please rate how much you agree with each of these statements, with 7 being strongly agree and 1 being strongly disagree (N/A means not applicable)	Scale							
		Strongly disagree						Strongly agree	N/A
a	It was easy to collaborate with other participants	1	2	3	4	5	6	7	
b	The tools facilitated collaboration	1	2	3	4	5	6	7	
c	The view / display facilitated working as a team	1	2	3	4	5	6	7	
d	We were able to finish the task	1	2	3	4	5	6	7	
e	Please suggest any changes to the tools / setup that we could make to improve the collaborative experience.								

Task 4

	Please rate how much you agree with each of these statements, with 7 being strongly agree and 1 being strongly disagree (N/A means not applicable)	Scale							
		Strongly disagree						Strongly agree	N/A
a	It was easy to collaborate with other participants	1	2	3	4	5	6	7	
b	The tools facilitated collaboration	1	2	3	4	5	6	7	
c	The view / display facilitated working as a team	1	2	3	4	5	6	7	
d	We were able to finish the task	1	2	3	4	5	6	7	
e	Please suggest any changes to the tools / setup that we could make to improve the collaborative experience.								

Appendix C (Continued)



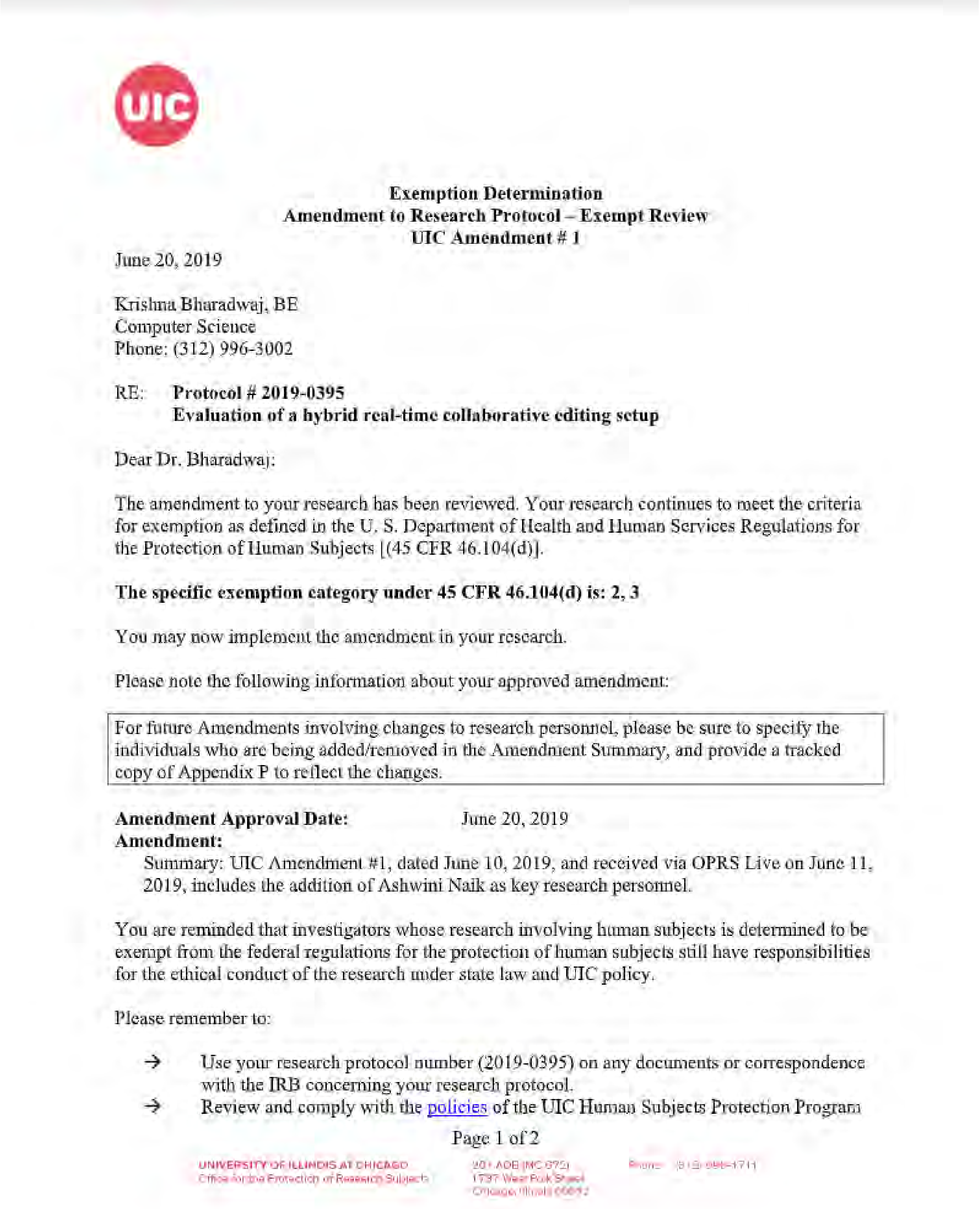
Please rate how much you agree with each of these statements, with 7 being strongly agree and 1 being strongly disagree (N/A means not applicable)	**Scale**							
	Strongly disagree						**Strongly agree**	N/A
Shared views and interactions for Task 3 and Task 4 (Compared to separate views of Task 1 and Task 2) made it easier to interact / communicate with other participants	1	2	3	4	5	6	7	
Shared views and interactions made it easier to work on Task 3 and Task 4 (Compared to working on Task 1 and Task 2)	1	2	3	4	5	6	7	

Please let us know if you have any comments about the collaborative tools used in this study.

Appendix D

IRB APPROVAL

Appendix D (Continued)



Exemption Determination
Amendment to Research Protocol – Exempt Review
UIC Amendment # 1

June 20, 2019

Krishna Bharadwaj, BE
Computer Science
Phone: (312) 996-3002

RE: **Protocol # 2019-0395**
Evaluation of a hybrid real-time collaborative editing setup

Dear Dr. Bharadwaj:

The amendment to your research has been reviewed. Your research continues to meet the criteria for exemption as defined in the U. S. Department of Health and Human Services Regulations for the Protection of Human Subjects [(45 CFR 46.104(d)].

The specific exemption category under 45 CFR 46.104(d) is: 2, 3

You may now implement the amendment in your research.

Please note the following information about your approved amendment:

For future Amendments involving changes to research personnel, please be sure to specify the individuals who are being added/removed in the Amendment Summary, and provide a tracked copy of Appendix P to reflect the changes.

Amendment Approval Date: June 20, 2019
Amendment:
Summary: UIC Amendment #1, dated June 10, 2019, and received via OPRS Live on June 11, 2019, includes the addition of Ashwini Naik as key research personnel.

You are reminded that investigators whose research involving human subjects is determined to be exempt from the federal regulations for the protection of human subjects still have responsibilities for the ethical conduct of the research under state law and UIC policy.

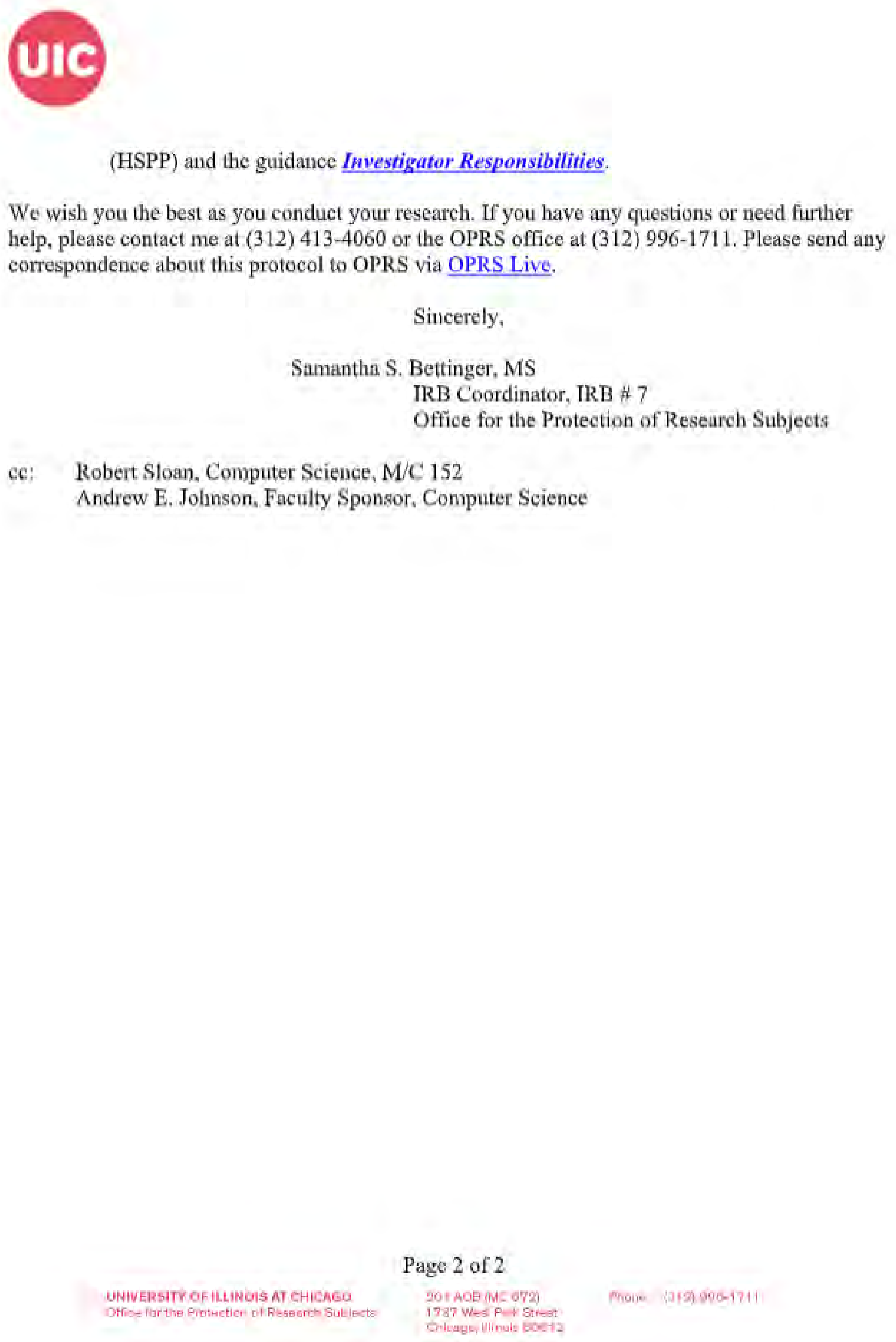
Please remember to:

→ Use your research protocol number (2019-0395) on any documents or correspondence with the IRB concerning your research protocol.
→ Review and comply with the policies of the UIC Human Subjects Protection Program

Page 1 of 2

UNIVERSITY OF ILLINOIS AT CHICAGO
Office for the Protection of Research Subjects
201 AOB (MC 672)
1737 West Polk Street
Chicago, Illinois 60612
Phone: (312) 996-1711

Appendix D (Continued)



(HSPP) and the guidance ***Investigator Responsibilities***.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact me at (312) 413-4060 or the OPRS office at (312) 996-1711. Please send any correspondence about this protocol to OPRS via OPRS Live.

Sincerely,

Samantha S. Bettinger, MS
IRB Coordinator, IRB # 7
Office for the Protection of Research Subjects

cc: Robert Sloan, Computer Science, M/C 152
Andrew E. Johnson, Faculty Sponsor, Computer Science

Page 2 of 2

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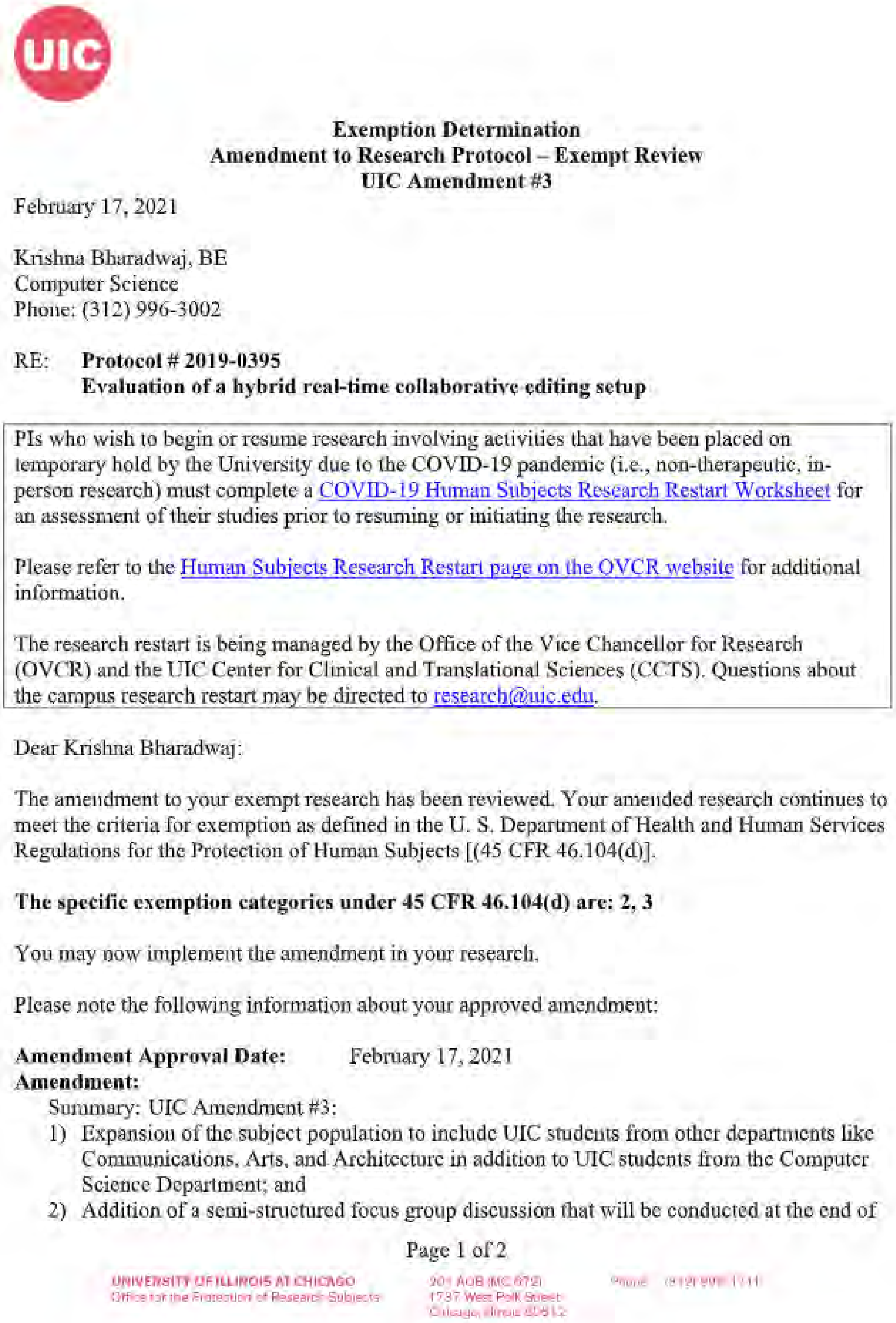
Appendix D (Continued)



UIC

Exemption Determination
Amendment to Research Protocol – Exempt Review
UIC Amendment #3

February 17, 2021

Krishna Bharadwaj, BE
Computer Science
Phone: (312) 996-3002

RE: **Protocol # 2019-0395**
Evaluation of a hybrid real-time collaborative editing setup

PIs who wish to begin or resume research involving activities that have been placed on temporary hold by the University due to the COVID-19 pandemic (i.e., non-therapeutic, in-person research) must complete a COVID-19 Human Subjects Research Restart Worksheet for an assessment of their studies prior to resuming or initiating the research.

Please refer to the Human Subjects Research Restart page on the OVCR website for additional information.

The research restart is being managed by the Office of the Vice Chancellor for Research (OVCR) and the UIC Center for Clinical and Translational Sciences (CCTS). Questions about the campus research restart may be directed to research@uic.edu.

Dear Krishna Bharadwaj:

The amendment to your exempt research has been reviewed. Your amended research continues to meet the criteria for exemption as defined in the U. S. Department of Health and Human Services Regulations for the Protection of Human Subjects [(45 CFR 46.104(d)].

The specific exemption categories under 45 CFR 46.104(d) are: 2, 3

You may now implement the amendment in your research.

Please note the following information about your approved amendment:

Amendment Approval Date: February 17, 2021
Amendment:

Summary: UIC Amendment #3:

1) Expansion of the subject population to include UIC students from other departments like Communications, Arts, and Architecture in addition to UIC students from the Computer Science Department; and
2) Addition of a semi-structured focus group discussion that will be conducted at the end of

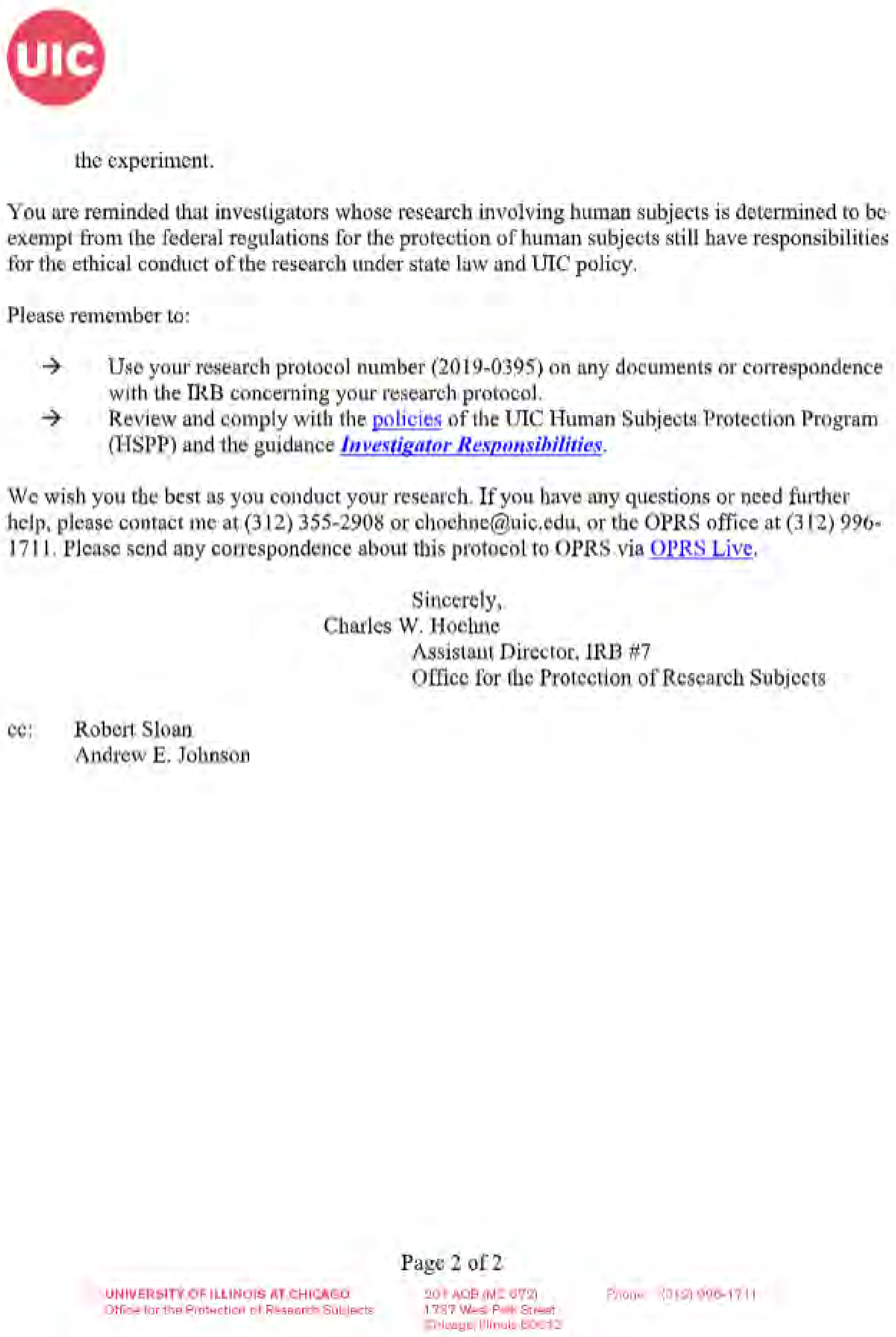
Page 1 of 2

UNIVERSITY OF ILLINOIS AT CHICAGO
Office for the Protection of Research Subjects

201 AOB (MC 672)
1737 West Polk Street
Chicago, Illinois 60612

Phone (312) 996-1711

Appendix D (Continued)



the experiment.

You are reminded that investigators whose research involving human subjects is determined to be exempt from the federal regulations for the protection of human subjects still have responsibilities for the ethical conduct of the research under state law and UIC policy.

Please remember to:

- → Use your research protocol number (2019-0395) on any documents or correspondence with the IRB concerning your research protocol.
- → Review and comply with the policies of the UIC Human Subjects Protection Program (HSPP) and the guidance ***Investigator Responsibilities***.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact me at (312) 355-2908 or choehne@uic.edu, or the OPRS office at (312) 996-1711. Please send any correspondence about this protocol to OPRS via OPRS Live.

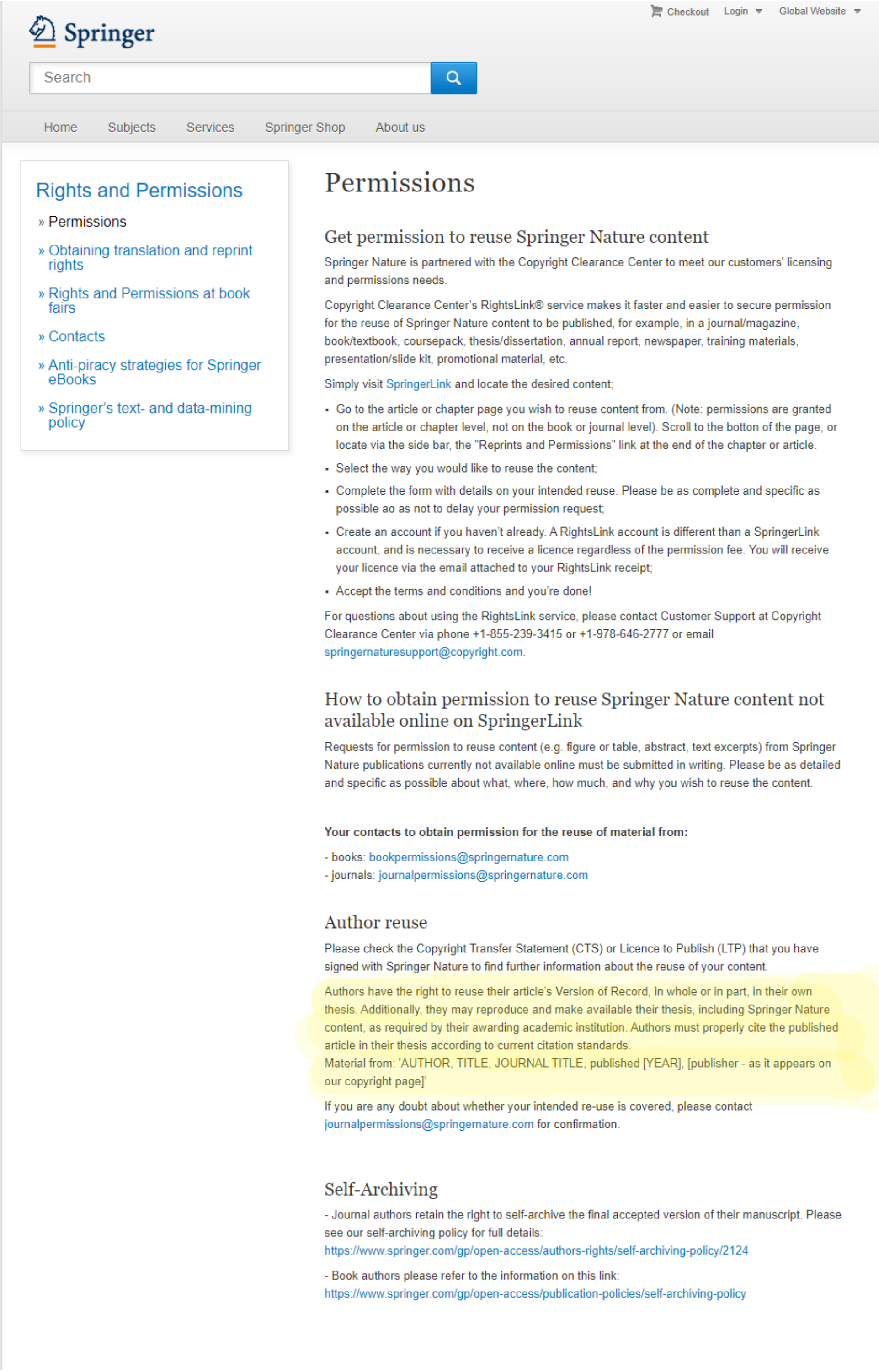
Sincerely,
Charles W. Hoehne
Assistant Director, IRB #7
Office for the Protection of Research Subjects

cc: Robert Sloan
Andrew E. Johnson

Appendix E

AUTHOR REUSE NOTICE FROM SPRINGER

Appendix E (Continued)



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VITA

NAME	Krishna K N Bharadwaj
EDUCATION	M.S., Computer Science, University of Illinois at Chicago, 2015 B.E., Computer Science, Visveswaraya Technological University, 2007
TEACHING	Teaching Assistant (Computer Graphics CS425), Department of Computer Science, UIC (Spring 2021) Lecturer, Department of Computer Science, National Institute of Engineering, India (Fall 2008 - Spring 2012)
PUBLICATIONS	Bharadwaj K., Johnson A.E., “A Hybrid Collaborative Virtual Environment with Heterogeneous Representations for Architectural Planning”, Gao H., Wang X., Iqbal M., Yin Y., Yin J., Gu N. (eds) Collaborative Computing: Networking, Applications and Worksharing. CollaborateCom 2020. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 350 Bharadwaj, K., Flores, S., Rodriguez, J., Long, L., Marai, G. E., “Developing a Scalable SNMP Monitor”, IEEE International Parallel and Distributed Processing Symposium, Chicago, IL, pp. 1043-1047, May 23rd, 2016. http://dx.doi.org/10.1109/IPDPSW.2016.32 Kirshenbaum, N., Kobayashi, D., Belcaid, M., Leigh, J., Renambot, L., Burks, A., Bharadwaj, K., Long, L., Brown, M., Haga, J., North, C., “The Smart Amplified Group Environment”, 4th Workshop on Immersive Analytics: Envisioning Future Productivity for Immersive Analytics, CHI 2020, Honolulu, HI, April 26th, 2020. Leigh, J., Belcaid, M., Kobayashi, D., Kirshenbaum, N., Wooton, T., Gonzalez, A., Renambot, L., Johnson, A., Brown, M., Burks, A., Bharadwaj, K., Nishimoto, A., Long, L., Haga, J., Burns, J., Cristobal, F., McLean, J., Pelayo, R., “Usage Patterns of Wideband Display Environments In e-Science Research”, Development and Training, 15th IEEE International Conference on e-Science, (eScience 2019), San Diego, CA, September 24th, 2019.

Doshi, V., Tuteja, S., Bharadwaj, K., Tantillo, D., Marrinan, T., Patton, J., Marai, G.E., “StickySchedule: An Interactive Multi-user Application for Conference Scheduling on Large-scale Shared Displays”, Proceedings of the 6th ACM International Symposium on Pervasive Displays (PerDis ’17), Lugano, Switzerland, June 7th, 2017.

T. Luciani, J. Trelles, C. Ma, A. Burks, M. Thomas, K. Bharadwaj, S. Singh, P. Hanula, L. Di, G.E. Marai, “Multi-scale Voronoi-based ACT Assessment”, IEEE VGTC VPG International Data-Visualization Contest, Baltimore, MD, USA. Honorable Mention. Oct. 2016.

Marrinan, T., Aurisano, J., Nishimoto, A., Bharadwaj, K., Mateevitsi, V., Renambot, L., Long, L., Johnson A., Leigh, J., “SAGE2: A New Approach for Data Intensive Collaboration Using Scalable Resolution Shared Displays”, In Proceedings of the 10th IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing, Miami, FL, pp. 177 - 186, October 22nd, 2014.