A Hybrid Collaborative Virtual Environment with Heterogeneous Representations for Architectural Planning

Krishna Bharadwaj(✉) and Andrew E. Johnson

University of Illinois at Chicago, Chicago, USA
{kbhara5,ajohnson}@uic.edu

Abstract. We developed a collaborative virtual environment for architectural planning that facilitates groups of people to work together using three different interfaces. These interfaces enable users to interact with the scene with varying levels of immersion and different interaction modalities. We conducted a user study to gauge the general usability of the system and to understand how the different interfaces affect the group work. In this paper we present the architecture of the system along with its different interfaces. We also present the user study results and the insights we gained from the study.

Keywords: Group work · Collaborative environments

1 Introduction

Improvements in network connectivity and advances in web technology have made it possible for people from across the globe to partner up with one another for working on large projects through remote collaboration. We see that more and more project teams, from both industry as well as academia, are becoming geographically distributed. As a result, we see an increase in efforts being made to come up with collaborative environments that support such large distributed groups to work together. Initially such collaborative work was limited to working on textual data but off late attempts are being made to support collaboration over data of graphical nature, such as geo-data [7] for mapping events, spatial 3D data [2,8] for sculpting of 3D models, architectural planning [1] and so on. A few of these emphasize on remote collaboration while others are more geared towards collocated collaboration.

We have developed a hybrid collaborative virtual environment for architectural planning, in that it supports both collocated as well as remote collaboration. The system consists of three different interfaces, namely a 2D interface, a 3D interface, and an immersive VR (Virtual Reality) interface, all interacting with a virtual environment for architectural planning. All three interfaces are

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synchronised using a centralized server to enable real time remote collaboration between them. Further, the 2D and 3D interfaces are developed as custom applications on top of SAGE2 (Scalable Amplified Group Environment) [3] leveraging the affordances of SAGE2 for collocated collaboration. This allows more than one person to simultaneously interact with, and control, both of these interfaces. The VR interface has been developed, using Unity 3D game engine, for HMDs (Head Mounted Display). The 2D interface presents a monochromatic top view of the scene over a grid layout, mimicking a floor plan. The 3D interface presents an in-person perspective of the scene with a limited field of view, giving the users a driver-seat view of the scene. The VR interface presents a fully immersive 360° view through the HMD to the user interacting with it. All the three interfaces are complete applications 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.

The motivation for this amalgamation of interfaces with different perspectives and viewpoints is threefold. First, in a collaboration consisting of multiple sites and users, a practical issue is the availability of hardware and other resources at every site. For example, if the required hardware has a large physical footprint, such as a CAVE (Cave Automatic Virtual Environment), chances are that not every site will have access to it or some user might be away from the hardware (say, working from home) and hence may not have access to it. In such cases, a system that is flexible in its hardware and software requirements for allowing a user to participate in the collaborative session is desirable. Second, each representation i.e 2D, 3D, and immersive VR, has its own affordances and limitations with respect to interaction with data. For example, while it can be very easy for a user to quickly place furniture in a floor plan using a 2D interface (or even just to draw on an actual floor plan), some level of immersion in a 3D scene is preferable to assess whether there is enough room to "walk around" in the space being designed. Further, while the immersive VR gives the user a chance to interact with the space at full scale, it prevents them from participating in face to face interaction with other collocated members of the team, whereas a 3D interface supporting collocated collaboration could provide a middle ground in such a case. Hence, a system that supports multiple ways of interacting with data can help the users by compensating for the limitations of one interface with the affordances of another. Third, project team sizes can have a wide range with the teams being split into smaller groups of collocated people, spread geographically. A system that can support both collocated as well as remote collaboration can enable more people from such teams to take part in the collaboration. Hence, by making each interface complete with all the functionalities and designing the synchronization server to handle multiple instances of each interface, we hope this model will afford flexibility to the users at each site, in choosing an interface that is best suited for them to participate in the collaboration.

2 Related Work

2.1 Distributed Collaborative Virtual Environments

Recent years have seen an increase in distributed collaborative systems that allow multiple users to interact with, and in some cases edit, data in virtual environments. Okuya et al. [4] discusses such a system 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. Our proposed system, in contrast, provides heterogeneous representations to users at different sites. Pick et al. [5] present a system to combine IVR (Immersive Virtual Reality) 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. While our system presents users with heterogeneous representations, it ensures that every user is able to fully interact with the virtual environment, albeit with different interaction modalities.

2.2 Collaborative Environments with Asymmetric Viewpoints

A few collaborative virtual environments have incorporated asymmetric views or perspectives of the virtual world. CALVIN [6] 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. All instances are run in CAVEs. DollhouseVR [10] is another 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. Moreover, the system is intended for collocated collaboration. MacroScope [9] 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. Our proposed system, in comparison, combines different perspectives with multiple representations with the aim of complementing the limitations of each representation or perspective with the affordances of a different representation or perspective.

3 System

3.1 Functional Requirements for an Architectural Design Application

All the three different interfaces should incorporate all the functional requirements for editing the architectural design. Here we briefly describe these requirements to help the reader understand the implementation details of the different interfaces that are explained below. We decided to have a basic set of four types of elements as the building blocks of our 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 interface 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 interface 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. We developed the 2D and the 3D interfaces 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 interfaces, 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 interface to connect to the large display and interact with it. By making the 2D and the 3D interfaces be custom applications on top of SAGE2 we let SAGE2 handle multi-user interaction for 2D and 3D interfaces. As shown in Fig. 1, we developed a synchronization server that relays messages between all the instances of the three different interfaces 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 interface, the camera location and orientation of the 3D interface, 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 site is immediately replicated at all the sites. The position (and orientation) information of different users are used to animate their corresponding virtual representations at all the different sites.

This allows users to know where "within" the scene, each user is and what they are doing at any given point in time.

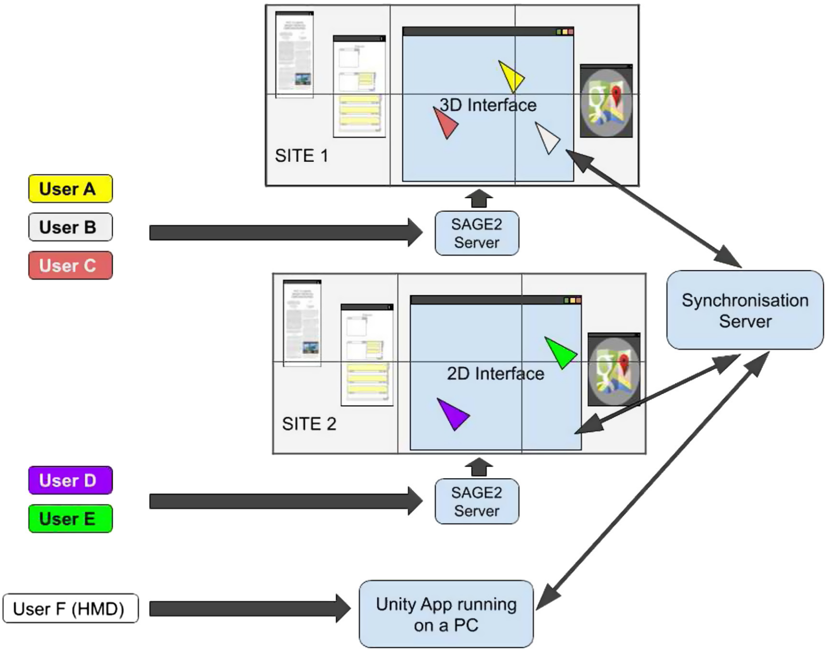

Fig. 1. Architecture of the collaborative setup showing one instance each of the 2D, 3D, and VR interfaces

3.3 2D Interface

The 2D interface 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 interface as shown in Fig. 2, 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 interface. The menu contains options to create walls, doors, windows, 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. We did not provide panning functionality in the 2D interface since the screen real estate in a SAGE2 environment is sufficiently large to present the layout in its entirety.

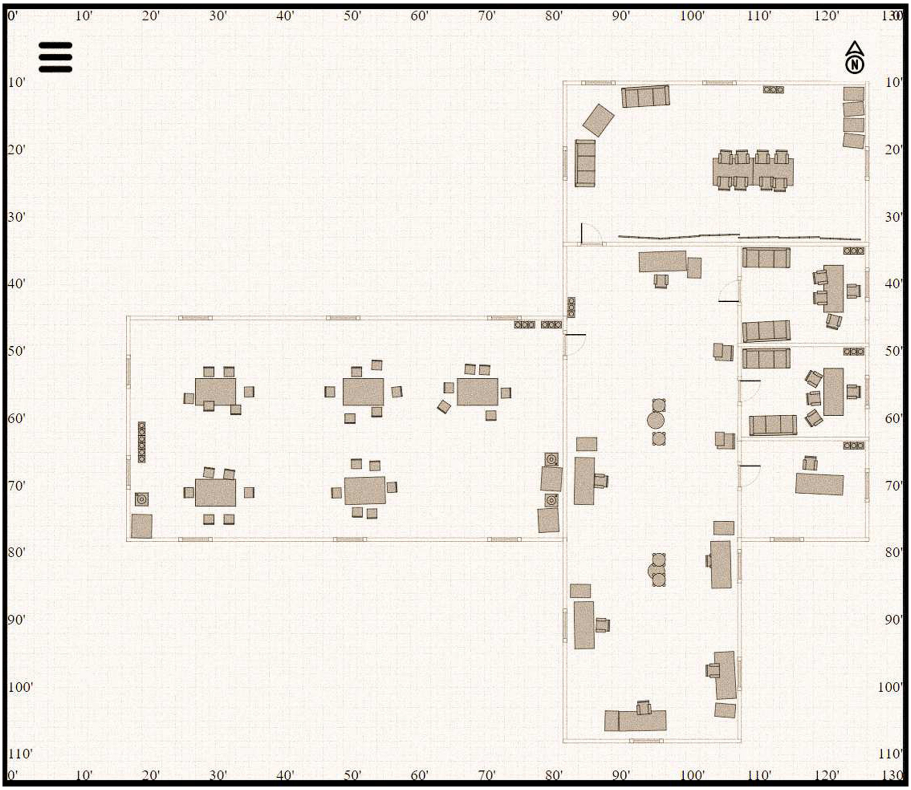

Fig. 2. 2D interface showing the floor plan of an office space.

In the 2D interface 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 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 interface, 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 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 interface, 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 interface as colored circles as shown in Fig. 5a. The color of a flag is chosen randomly by the interface 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.

Fig. 3. Two users interact with the 3D interface

3.4 3D and VR Interfaces

The 3D interface presents the users with an in-person perspective of the scene, rendered on a large display in a rectangular window as shown in Fig. 3, whereas the VR interface presents the same in-person perspective in a fully immersive head mounted display as shown in Fig. 4. 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 interface both in appearance as well as functionality, is provided in the 3D as well as the VR interfaces. Both of these interfaces also have “Selection”, “Wall Creation”, and “Door or Window” modes similar to the 2D interface, albeit with interaction metaphors that are more appropriate to 3D interaction. For example, unlike the 2D interface, 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.

The 3D interface 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. The VR interface 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 interfaces as shown in Fig. 5b and c. 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 interface 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.

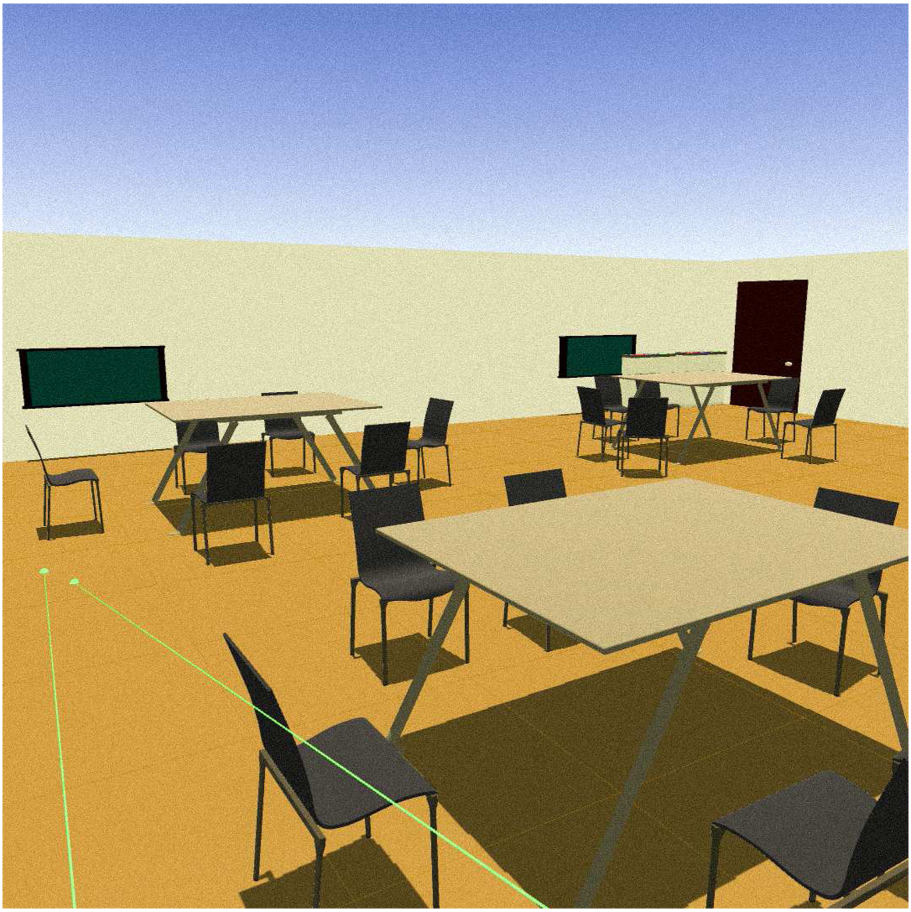

Fig. 4. VR View of a part of the designed space

The 3D interface 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 interface within the scene (the "drive through the scene" metaphor of the 3D interface is relatively slower than the VR users' ability to teleport instantly to any part of the scene or the 2D interface 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 interfaces 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 we created representations as follows: The 2D interface serves as a top view and this is reinforced in the way the VR user as well as the 3D interface's camera within the scene are depicted in the 2D interface as shown in Fig. 5a. The VR user's representation shows a human icon wearing a VR headset, from the top view. The camera of the 3D interface 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 interfaces, the mouse pointers of users from the 2D interface are represented using 3D arrows in the scene and they continuously move about within the scene (similar to the "God-like" interaction technique [11]) following the pointer movements of users within the grid of the 2D interface. The VR user is represented as an avatar (Fig. 5b) in the 3D interface, with two rays attached, that reflect where the VR user is pointing the controllers. The camera of the 3D interface is represented as a rectangular

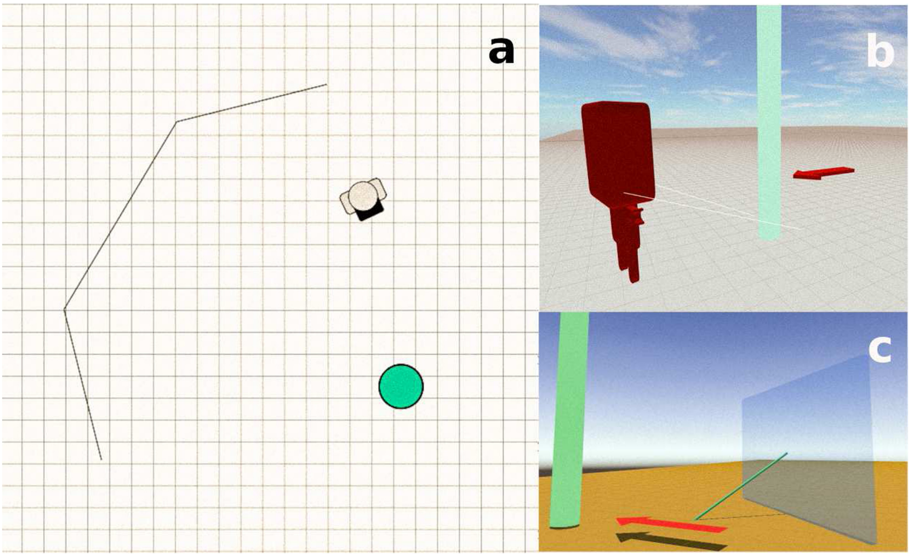

Fig. 5. a. 2D interface showing 3D user and VR user and a flag. b. 3D interface showing 2D user's pointer as an arrow and VR user as an avatar with the same flag shown as a column. c. VR interface showing 2D user's pointer as an arrow and 3D user as a 3D window with a pointer coming out of it and the flag shown as a column

window in the VR interface (Fig. 5c). Whenever a user at the 3D interface has their pointer on the interface 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.

4 Evaluation

To get an idea of the general usability of our system and to gain insights into how the differences in representations across the interfaces affect the group work, we conducted a group user study. In the study we asked a group of participants to use all three of the interfaces 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 interfaces), with each trial involving 4 participants. One participant interacts with the 2D interface, and one interacts with the VR interface through an HMD, and two participants interact with the 3D interface. Even though both 2D and 3D interfaces are capable of handling multiple users in a collocated collaborative manner, due to lack of availability of participants we decided to limit collocated collaboration to only one of those interfaces in the study. Each interface was situated in a different room within our lab to reflect a real remote collaboration scenario. 3D interface was presented on a 23.8 × 6.7 foot (37.3 megapixel) large display running a SAGE2 instance. The display was situated in a 41 × 24 foot room. 2D interface was presented on a 13.4 × 5.7 foot (12.6 megapixel) large display running a SAGE2 instance. The display was situated in a 41 × 28 foot room. The participants were seated in front of these large screen displays and interacted with them using laptops. In a third room, the VR interface was presented using an HTC vive HMD to the user. The VR user had a 10 × 10 foot 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 interface 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. We set a time limit of 75 min to give the participants enough time to work, however they could finish earlier. Every session was audio and video recorded. Additionally, we recorded the head orientation of the users at the 3D interface. 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

We 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 our system including its affordances for group communication and collaboration. Table 1 shows the results we 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 interface on navigation and object manipulation metrics. We had also asked descriptive questions towards understanding any issues the participants might have had in interacting with the system. Some of the answers we obtained helped us understand those lower scores. On a few occasions when the view had too many closely placed objects, the 3D interface 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 we implemented at the 3D interface and has been fixed since the running of the user study. The different representations of different interfaces to achieve co-presence did not impede the collaboration as we can see from the results. In fact, we 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.

Table 2 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 1.

Table 1. Average scores of metrics for usability, co-presence awareness, and ease of collaboration (on a scale of 1–5)

Metric	2D Interface	3D Interface	VR Interface
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

Table 2. 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

The chart in Fig. 6 shows a breakup of all the objects that were created by different participants (we combine the numbers of both the collocated participants at the 3D interface, 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 interface. Through the recording we observed that, at the beginning of each the participants briefly 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 interface. We also noticed that, soon after creating the walls, the participants at the 2D interface would proceed to place the doors and windows on them. This can also be noted from the break down shown in Fig. 6.

We 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 we used the logs to find the break up of these edits based on "location" within the design space such

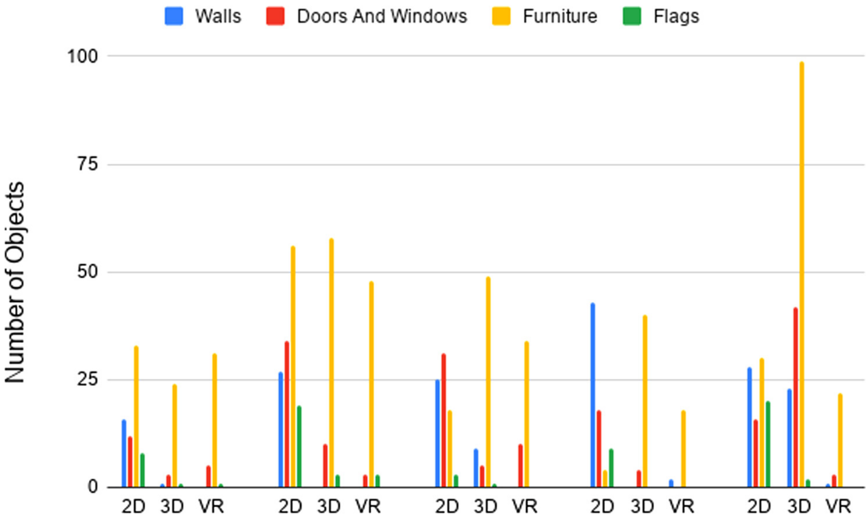

Fig. 6. Break down of all the design objects created by different participants

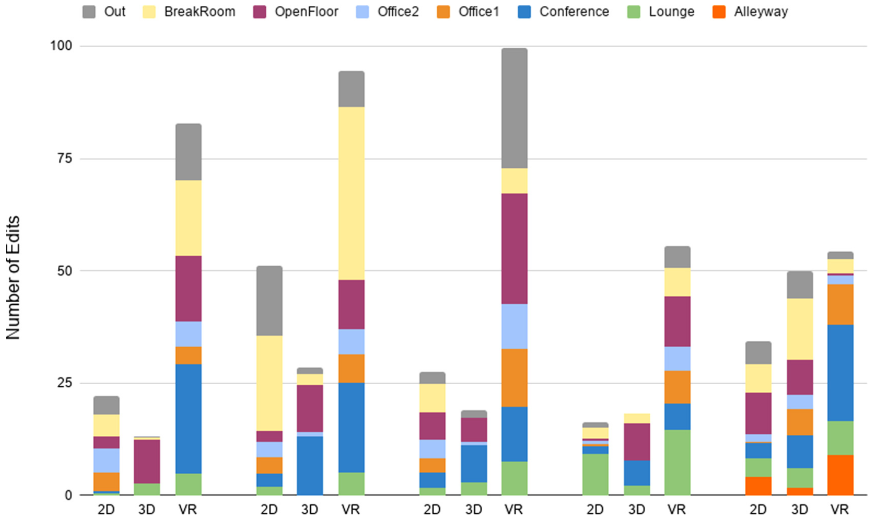

Fig. 7. Break down of edits done by different participants at different locations (Out refers to outside the boundaries of the floor plan)

as “Lounge Area” and so on. Figure 7 shows the results. We 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 interfaces.

5 Discussion

From the video recordings of the sessions, we observed a few elements of the collaborative exchanges that happened between the participants. First, by the end of the practice session the participants concluded that certain aspects of the interfaces 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 interface 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. We 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. Second, even though all interfaces are equipped with all the functionalities needed to complete the task at hand individually, the affordances of the different interfaces favored particular interfaces for specific functionalities. As we noted 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. We 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. Third, 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 s) 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 Fig. 6) to either draw each others' attention or to help others to navigate to a location. All these points help to reinforce our initial assumption that combining different interfaces with heterogeneous representations does not negatively affect the collaboration, but helps in making the group work more flexible.

6 Conclusion

We presented a hybrid collaborative virtual environment for designing architectural spaces that facilitates users to collaborate using different representations and asymmetric views. The results from a user study that we conducted demonstrated that our system enables users to freely collaborate despite having differences in interface affordances and scene representations. The results also bolstered our initial intuitive assumption that the limitations of one representation would be compensated by the affordances of another in carrying out the group task. As a future work, we plan to conduct a more detailed user study to gain insights into collaboration patterns that might emerge from our system.

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