Improving Information Sharing and Collaborative Analysis for Remote GeoSpatial Visualization Using Mixed Reality

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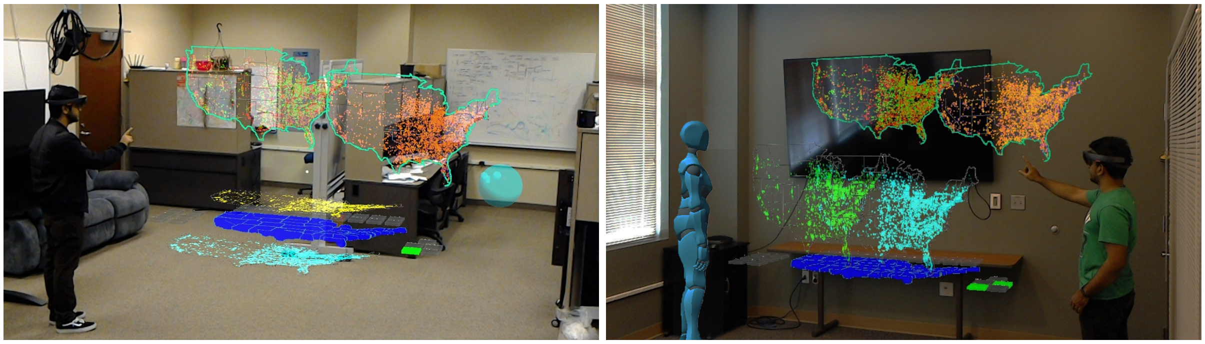

Figure 1: Two users perform collaborative visualization tasks at different sites connected to our campus wireless network. Our remote system supports interactive, immersive, and intuitive collaboration functions for users to perform and share the sensemaking process, which enhances the information sharing and collaborative analysis experiences compared to traditional desktop visualizations. In this example, the shared space contains the 3D map and two visualization layers with cyan outlines, indicating that they were created by the user represented by the same avatar color. Each user also has his private space where additional holograms are only visible to them: the yellow and cyan layers on the floor for the left user, and the green and cyan layers floating in the air for the right user.

Abstract

Remote collaboration systems allow users at different sites to perform joint tasks, which are required by many real-life applications. For example, environmental pollution is a complex problem requiring many kinds of expertise to fully understand, as pollutants disperse not only locally but also regionally or even globally [61,62]. This paper presents a remote collaborative visualization system through providing co-presence, information sharing, and collaborative analysis functions based on mixed reality techniques. We start with developing an immersive visualization approach for analyzing multi-attribute and geo-spatial data with intuitive multi-model interactions, simulating co-located collaboration effects. We then go beyond by designing a set of information sharing and collaborative analysis functions to support different users to share and analyze their sensemaking processes collaboratively. We provide example results and usage scenario to demonstrate that our system enables users to perform a variety of immersive and collaborative analytics tasks effectively. Through two small user studies focusing on evaluating our design of information sharing and system usability, the evaluation results confirm the effectiveness of comprehensive sharing among user, data, physical, and interaction spaces for improving remote collaborative analysis experience.

Index Terms: Human-centered computing—Visualization—Visualization techniques; Human-centered computing—Visualization—Visualization design and evaluation methods

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1 Introduction

As hardware has been improving on a fast pace over the past decade, remote collaboration has been identified for a long time as an important research problem in fields such as visualization, computer-supported cooperative work (CSCW), and augmented reality (AR) [31,35,42]. In particular, collaborative visualization and analysis allows multiple users to see and interact with data jointly. Such systems are required to perform essential tasks that one person cannot, or to discuss, explain and confirm analysis results with collaborators. While majority visualization techniques are developed for a single user, there are already a number of early research successes [9,20,30,32–34,37,59,63]. Effective collaboration techniques involving of design, communication, joint analytics, and decision making can benefit various remote collaboration applications.

Collaborative analysis is especially interesting to visualization, as "decision-making based on data analysis is often the result of a collaborative effort" [31]. The past efforts mainly focus on web-based systems or large displays, as these settings are often more suitable for collaboration with larger rendering spaces than desktop computers. Now with the latest advances of mixed reality (MR) and emergence of related interdisciplinary research fields, there are important open problems involving social interaction, communication, and effective usage of spaces that need to be studied to better support collaborative visualization. In addition, new technological possibilities and applications are still just starting to emerge.

The driven force of this work is a real-life application, environment protection, which requires collaboration by researchers from interdisciplinary fields, policy makers, companies, and even citizens. Our main dataset is the Toxics Release Inventory (TRI) from the United States Environmental Protection Agency (EPA). TRI is a comprehensive geo-spatial dataset with information about hundreds of chemicals. The results of toxic spreading into the environment (i.e. air, water, and land) are also affected by the geo locations. Traditionally, users of TRI at different sites have to work by tediously overlaying information on maps, making notes, talking over phone, and sending reports back-and-forth.

In this work, we explore using MR to develop new collaborative analysis functions with immersive visualization and multi-model interactions for remote collaboration system. Different from previous work on collaborative visualization, our immersive visualization mixes virtual information with physical environments using MR, without requiring additional physical displays such as monitors or touch surfaces. Specifically, we study how immersive approaches can provide more effective collaborative analysis system by improving information-sharing and interactive analysis regarding to data handling, sensemaking process, user behaviors, and the physical environments within which the analyses are performed.

Our immersive approach simulates the basic work process of geospatial analytics, and enhance the process with more analysis, co-presence, and collaboration capabilities. Using MR, we embed virtual information into physical environments to provide a more extensible workspace to each user. We develop a real-time collaboration system and connect remote collaborators into the workspace as virtual avatars to improve a shared sense of co-presence. Our system provides both private and shared visualization sessions, and allows users to transition in between easily. Lastly, our system collects user history data in all domains of data, interaction, and MR environment and provides each user with better contexts of collaboration through 3D history traces and interaction provenance visualization.

Our approach is generally applicable to all geospatial visualization applications. We evaluate our prototype system through an usability study and a study on collaborative interaction and information sharing. Our results demonstrate that immersive spaces are helpful for creating shared situation awareness in remote and collaborative settings.

The remainder of this paper is organized as follows. We review the related work in Section 2. Section 3 describes the requirements and our design principles of remote collaboration system for geospatial data visualization. We present our system architecture in Section 4, immersive visualization approach in Section 5, and collaborative analysis and information sharing functions with MR in Section 6. We then present the example results in Section 7, evaluation in Section 8, and discussions in Section 9. Finally, Section 10 concludes the paper and describes our future work.

2 Related Work

We review the related work from the aspects of collaborative visualization, collaborative AR/VR techniques, and immersive analytics.

2.1 Collaborative Visualization

Collaborative sensemaking can play an important role in visualization as it allows a group of people to analyze data jointly and effectively [18, 24, 30]. Facilitating collaboration among multiple users working on the same problem has been identified as one of the grand challenges for visualization research [58]. As pointed out by Isenberg *et al.* [31], collaborative visualization is important as it enhances traditional visualization by bringing together experts to contribute towards common goal of understanding data under consideration and resolving ambiguity in data interpretation. Several guidelines and design considerations regarding to collaborative visual analytics have been explored [26,30,45,58]. However, few past works have focused on collaborative and immersive environments for abstract data visualization.

Collaboration systems can be classified by the locations of use (i.e. co-located vs. remote) and by the time aspect (i.e. synchronous and asynchronous). For example, Balakrishnan *et al.* [4] explored how teams shared visualizations remotely to solve a complex problem. They found that visualization was the most effective when collaborators had full access to the shared visualization and could synchronously interact with it. Similarly, Keel's system [34] for collaborative visual analytics provided awareness by inferring information from a team member's workspace and suggested relevant data to remote collaborator, which allowed implicit information sharing to converge individual contributions of team members. Brennan et al. [9] provided the functions of explicit sharing and merging of data views during distributed visual analysis, so that collaborators could work alone first and switched to a shared view for joint sensemaking later. In this work, we focus on a combination of remote and synchronous collaboration.

For effective collaboration, visualization systems should also support human processes involving resource sharing, coordination, collaboration and attempts at reproducible analyses. For these reasons, a substantial amount of research has been dedicated to support *provenance*, which considers history of changes and advances throughout analysis process. Different aspects of the cognitive and interactive processes of discovery and exploration can be included as well as the computational sequences traversed to arrive at insights. Prior surveys have presented definitions, categorization, opportunities and challenges for analytical provenance [27, 49, 67]. Several systems and tools have also been developed to help analysts record both computational workflows [5, 17] and reasoning processes [21, 25]. For example, *VisTrails* [5] tracked steps of computational workflow during scientific data analysis and visualization, and then provided graphical representations of workflow using node diagrams and intermediary visual outputs. Their results demonstrated that the user behavior revealed aspects of analytic process and reasoning and thus valuable in making overall sense of the data. Our work also provides visualization of interaction history for analyzing and sharing the sensemaking process.

2.2 Collaboration in AR/VR Environments

Augmented reality (AR) and virtual reality (VR) can be used to create various collaboration environments, which allow users to share and interact with virtual objects in real time. Immersive environments have been used to create unique collaborative experiences [3, 8, 13, 35, 51, 66].

A recent survey [35] pointed out several important topics in AR including collaboration. During the past, both co-located and remote AR collaboration systems have been developed. For example, Benko et al. [7] supported multiple users to explore scaled and full-size representations of an archaeological dig. Nilsson et al. [48] presented a co-located AR system for supporting joint planning tasks by providing shared organization-specific views for police and military personnel. Dong and Kamat [19] introduced a tabletop fiducial AR system for co-located collaboration. More recently, Butscher et al. presented an approach of AR above the tabletop (ART) for collaborative analysis of multidimensional data [10].

Several previous works demonstrated that AR can help improve the sharing of situational and navigational information among users. Lukosch et al. [42] pointed out the useful features of AR technology for collaboration, such as reproducing some of the spatial cues used in face-to-face collaboration that are normally lost in remote conferencing systems, increasing social presence compared to other technologies, and allowing remote collaborators to interact naturally in the local user's real environment.

We have found two existing techniques on using AR/VR for collaboration to be especially valuable. First, multi-scale interaction ensures smoother collaboration among users at different environments [14, 39], for example, between outdoor wearable AR users and indoor users using a tabletop projector [55]. Recently, Mini-Me [50] showed that using adaptively sized avatars can improve social presence and overall experience of MR collaboration. Second, effective collaboration systems often provide visual cues of embodiment, which are virtual representations of collaborators' physical or activity states for improving awareness during remote collaborations [6, 29]. Examples techniques have been developed for sharing information about the state of users' limbs, including arms [22, 56], hands [53, 57] and feet [2]. The effects of gaze tracking [28], shared virtual landmarks (SVLs) [46] and redirecting of virtual avatars in distributed AR meetings [36] have also been explored.

Based on these principles, we have designed our system with visual cues of embodiment to improve remote collaboration on visualization tasks. Unlike previous works in AR/VR, we have also added methods to visualize provenance information in the immersive environments to assist collaborative analysis.

2.3 Immersive Analytics

Immersive analytics [11] extend the classical desktop visualization into a variety of new environments with AR and VR technologies. While still in its early stages, immersive analytics has attracted the interests from many researchers, as exemplified by many recent works on utilizing both virtual or physical 3D space to explore various data tasks and interactions, as well as evaluation studies on the effectiveness of these approaches [15, 38, 40, 60, 64, 65].

AR generally superimposes holograms with the environment around users and allows interaction with holograms and everyday objects. Microsoft HoloLens is a well-known example [12]. Compared to VR, AR is more suitable for real action with the integration of virtual information in real physical environments. For example, AR was used as a tool to support the collaboration between rescue services for the police and military personnel in a crisis management scenario [47]. AR techniques were used to support quick context-related information exchange for operational units in the security domain that work together in teams [16]. AR-based mobile assistance systems in context-based provision of facility-related information [43] were shown to minimize the intensive recall required in this domain. Mahfoud et al. [44] used immersive visualization for investigating abnormal events in heterogeneous, multi-source, and time-series sensor data. Recently, a toolkit for building immersive data visualizations based on the Unity development platform has been published [52]. According to our knowledge, we are among the early efforts of developing remote collaborative visualization system for data analysis tasks.

3 Requirements and Design of Remote Collaborative Visualization System

Geo-spatial analysis has been one important driving force of collaborative visualization system. We use the TRI dataset published by the environmental study from US Environmental Protection Agency (EPA), since TRI has created an unique research opportunity for collaborative visualization. Every year, EPA tracks toxic releases and publish TRI as the most comprehensive data product, which contains information about 650 toxic chemicals. These chemicals are manufactured, transported, used for various purposes, treated on- or off-site, and then released into the environment (i.e. air, water, and land). Companies, policy makers, researchers, and citizens have widespread needs to stay informed and have an up-to-date shared situation awareness of such toxic releases.

This application requires visual analytics tools to compare chemical distributions and search for correlations effectively, and to do so involving many stakeholders, and regionally, as well as nationally, in the future. To enable effective collaborative analysis capabilities, we have identified key requirements as the following.

- Design MR-based functions to visualize TRI data in ways that are not available in desktop settings, and enable effective visual analysis of multi-attribute, geo-spatial data through utilizing large 3D spaces and physical interactions.
- Enable real-time collaborative interaction, coordination and communication among all users.
- Emulate co-located collaboration by multiple remote users surrounding the same map, with suitable 3D immersive visualization and multi-model interaction functions integrating intuitive inputs of voice, gaze, and hand gestures.
- Design two types of spaces, private space for individual usage and shared space for joint analysis and discussion. Allow users to use both types of spaces concurrently, and switch among them freely for different user needs.
- Build collaborative analysis functions for sharing and visualizing both the data and the sensemaking process, which has been shown to improve the communication among a group of users from desktop visualization experiences.

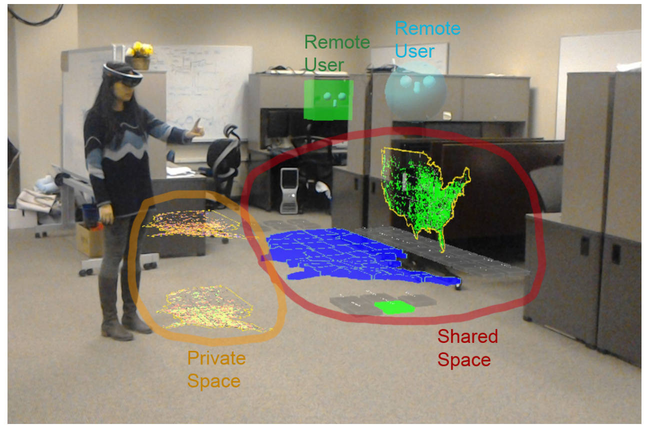


Figure 2: An example of our remote collaboration system, featuring private/shared spaces for joint data analysis. Visual cues, colors of map boundaries, are provided as indication of the owners.

4 System Architecture of Remote Collaboration

Based on the requirements of remote collaboration system described above, we have built a system supporting a flexible combination of visualization functions for both individual and collaborative users. The following presents the overall architecture of our system and the key components to support collaborative and co-present interactions.

4.1 Overall System Architecture

As shown in Figure 3, our system is consisted of a server and multiple HoloLens devices, all connected through a wireless network.

- The server is used to transfer various information between HoloLenses, and it is hidden from end users.
- Each user is equipped of one HoloLens device to perform immersive and collaborative analysis tasks.

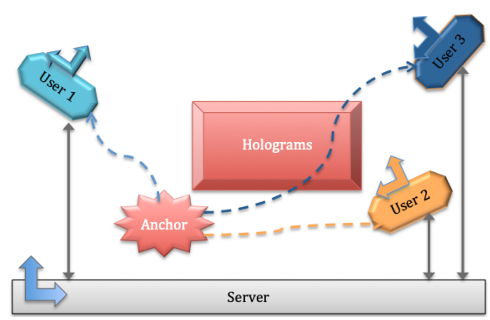


Figure 3: Illustration of our system architecture, where all users are registered in a shared virtual space using anchor points. The user locations, orientations, and paths in the physical space (shown in dashed lines) are all tracked and coordinated in the virtual space in real time.

The communication and networking is achieved through wireless network. All the HoloLenses are connected to the server, which joins all devices in the same online session in a virtual space and places the user at the central world anchor of that virtual environment when the user is first connected. The communications between any two HoloLenses are routed through the server, supporting different communication patterns such as one user sending information to other selective users or broadcasting to all users.

Our system is built upon Microsoft's HoloToolkit Sharing Service and Input System for Unity [1], which provide examples of sharing holograms and tracking of multiple people joining the session. The Sharing Service is built upon Unity's networking system, but customized for MR.

4.2 Coordination among Multiple Users

Since each HoloLens has an independent 3D coordination system, we need to align their systems with the virtual 3D space created by the server. With the alignment, we can register all the users in the same 3D coordination system and create co-present experience.

The coordination among multiple users is achieved through world anchors, which are special points in space. The locations of anchor points are sent to each user in a session, so that holograms can be placed in the same relative position for each user. Users are oriented within the virtual environment based on the assumption that the direction the user is initially facing is where they wish the central visualization to be located.

When the first user connects to the server, a world anchor is created to mark the position of the central visualization within the virtual space. The server uses the same world anchor to coordinate all users in the same virtual space. Once aligned, the head positions and orientations of all users are tracked and can be shared among all users. This is achieved by sending the updated position and orientation of each user in relation to the central world anchor.

Similarly, whenever a hologram (for visualizing anything such as users or data) is created and users wish to share it, a world anchor is generated and all other users can see it at the correct position. Any modification to location and rotation of the hologram are then applied to the world anchor and updated for all other users.

5 IMMERSIVE GEOSPATIAL VISUALIZATION&INTERACTION

Next, we present our immersive visualization method to support the exploration of geospatial, multi-attribute TRI data in this Section. Corresponding to geospatial data, our approach of immersive visualization features the usages of physical spaces and simulates the effect of people working around a map placed in front of them. The multi-attribute data can be overlaid on top of the map or visualized in the physical space around. We also use multi-modal interactions combining voice, gaze and hand gestures available with current MR devices to provide immersive interactions for users to move around and perform various analysis tasks.

5.1 Interactive 3D Map Foundation

We have created a 3D interactive map component as the foundation of the immersive visualization, shown in Figure 4. The map component can be horizontally displayed simulating a large map placed on a table or floor, or vertically displayed simulating the map posted on a wall. The map component can also be moved interactively with selecting and dragging interactions.

The map consists of individual 3D pieces, each for a state of USA. Each piece is created independently from outlining the boundary of the state and extruding along the z-axis as a 3D model. While the positions of the map pieces are fixed, the heights of individual state pieces can be altered based on selected attribute to visualize how much toxic chemicals are released compared to other states.

The map foundation also serves the interactive function to select different states. Each state can be interactively selected by pointing to and clicking the piece. We then use the selection results to filter the data to be visualized. As shown in Figures 4 and 5(b), the colors of the state pieces demonstrate the selection status - orange states are selected and corresponding data is shown.

5.2 Immersive Interaction Interface

To visualize the multi-attribute data, we adopt an interface for users to interact with data attributes easily. The interface is mainly generated with virtual blocks, placed on the top and sides of the 3D map, as they are buttons in the immersive system, shown in Figure 5(a). It also shows the overview of available attributes and whether they are selected or not by each user. We have divided the interactable interface into three sections. First section is based on pre-processing of the dataset – we provide users with 10 highly released toxic chemicals and also 10 most common industry types releasing these chemicals in huge amount. User can filter the dataset based on each of these chemicals or industries to compare, analyze and understand which states are releasing the toxic chemicals in the largest quantity. Interaction with menu buttons changes the height of individual state in the 3D map and also shows exact locations in form of data points on holographic layers.

Second section of interface is used to control sharing functions. In addition to voice commands for sharing different visualizations, we also provide interactive buttons to control the sharing. The colors of buttons signify the state of sharing. Here we have include buttons located on right side of 3D map to show data in form of varying heights of individual states based on their release amounts.

Finally, third section of interface is used to create additional holographic layers and apply multiple attributes available in the dataset. These buttons are located on left side of 3D map. Detail of holographic layer is described in the following.

5.3 Image Layers for Multi-Attribute Data

We provide interactive holographic layers of USA map consisting of outlines of the map and respective states. As the background of data, this transparent image outlines the state boundaries, allowing better see through effects when visualizing several data attributes as a stack of parallel layers.

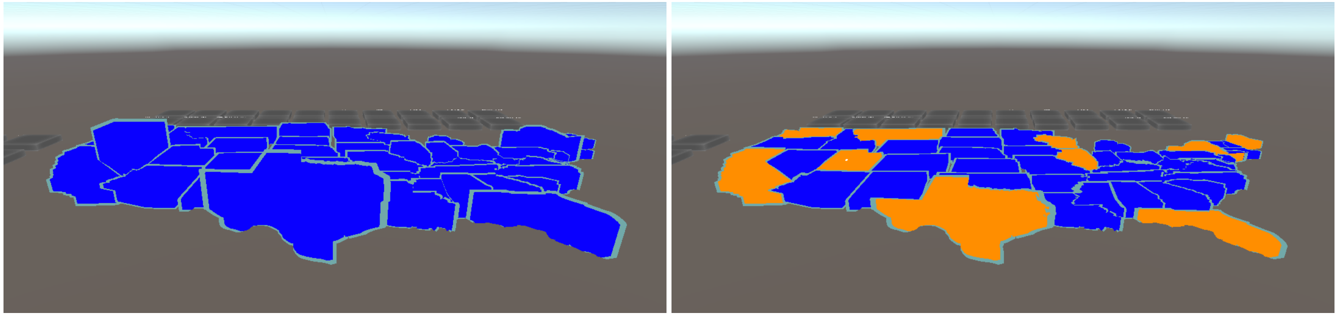
Each of these holographic layers can be used to visualize a combination of data selection with our interface, including the facility locations where carcinogenic chemicals are released, industries that comply with Clean Air Act, metal industries, industries owned by federal government, the top industry types releasing these chemicals in huge amount, list of top chemicals released, most toxic chemicals and different combinations of all above.

Our system supports multiple holographic layers for comparison purposes. Each layer can be independently filtered by combining different selection of chemicals and locations. Multiple layers can be interactively placed in the physical space, overlaid on the 3D map foundation, stacked onto each other, or laid out around the 3D map in various layouts with different rotation, scale and position. This allows users to perform a variety of visualization tasks.

Since our dataset involves over 81,000 facility locations spreading over 50 states in USA. To avoid system slow down due to rendering of so many data points over multiple holographic layers, we accelerate the point rendering using Unity3D's particle system. A particle system generally emits particles which can have shape like spheres or cones. They also have less of an impact on system performance because they do not contain collision boxes and can be referred to as a group instead of individual objects.

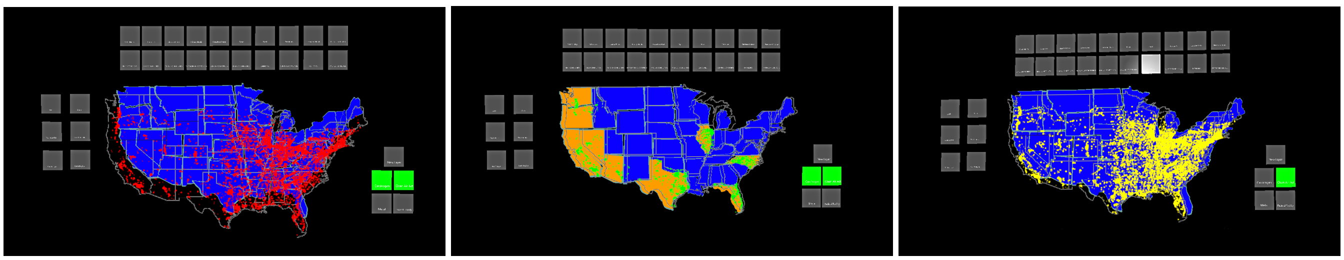
5.4 Immersive Interaction Functions

Our design of user interaction is to support users to combine multi-modal interactions including voice, gaze and hand gestures to perform tasks in the physical space with our immersive visualization



(a) (b)

Figure 4: The interactive 3D map foundation. (a) Varying heights of states in the 3D map where heights represent the aggregated release amounts of selected chemicals. (b) Filtering data for other visualization layers by air tapping individual states, with selected states shown in orange. The grey buttons in the distance surrounding the 3D map are for additional filtering combinations. Images are taken from Unity.



(a) (b) (c)

Figure 5: Examples of immersive visualization taken from Unity. All of our interactive 3D map and multi-attribute visualization layers can be interactively placed in the physical space, allowing users to work around using multi-model interactions. (a) Filtering holographic layer overlaid on the top of 3D map with 'carcinogenic' and 'clean air act' by air tapping the two buttons in green; (b) Selecting specific states for the data layer on the bottom; (c) Interacting with the system using hand gestures and gaze (one of top chemical button is highlighted in white when looked at).

system. All of our virtual elements in the system can be interacted as if they are actual objects in the physical space.

Specifically, all interactable holograms can be rotated, scaled, and moved within the shared virtual environment. To perform these interactions users must first say "move", "rotate", or "scale". Then users simply perform a pinch and dragging motion, otherwise known as the manipulation gesture, to manipulate the object. The magnitude of each interaction is based upon the distance that the hand moved from the start to the end of the gesture, which gives users control of how much they want to modify the object. In addition, users can enable or disable various visual cues using combination of voice commands and gaze direction, such as avatars of other collaborators and their gaze locations for understanding their point of interest.

6 Information Sharing Enabled by Mixed Reality

As pointed out by [31], effective information sharing is useful only if sufficient context is given so that collaborators may understand and apply it appropriately. We strive to improve information sharing during collaboration in the rich environment utilizing the MR features. Specifically, we share information collected comprehensively from the spaces of user, physical environment, and data domains.

- User space: Every user has his or her private space, in addition to a shared space available to all users. The methods of information sharing are different based on the user space, while we allow flexible switch between private/shared spaces.
- Physical space: Information sharing in the physical space is often missing in previous collaborative visualization approaches. We provide sharing of a series of user history information including user positions and orientations during their interactive visualization process.
- Data space: We explore the design of data provenance in MR to visualize how multi-attribute data has been involved during the sensemaking process.

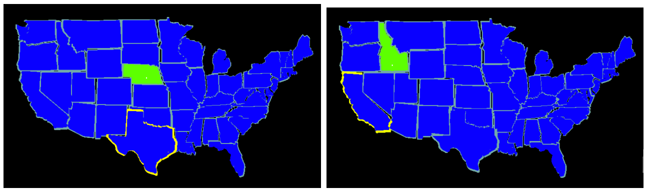
This section presents several components of information sharing during or after the exploration process. We first describe our sharing mechanism for controlling user and physical spaces. Then we present the methods of revisit of history traces and interaction provenance for improving information sharing in the combined physical and data spaces.

6.1 Improving Co-Present Experience in Collaboration

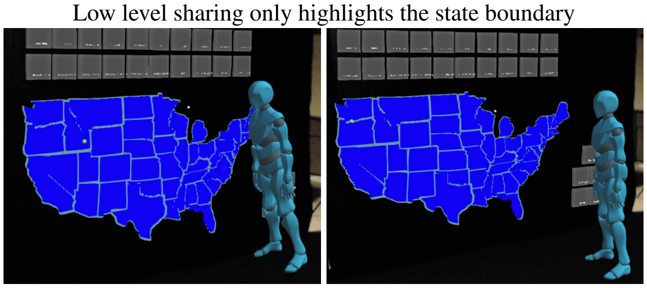
To improve the co-presence experience, we create virtual representations of remote users with avatars. Several avatars with different bodies or heads are used to differentiate the users. We generally prefer the full body avatars for emphasizing the co-presence of remote collaborators, and head shapes for indication of the users' positions and orientations.

We continuously update the avatars with the correct position and orientation to provide the context of what people are referring to. This is achieved by sending messages over the network whenever a remote user adjusts their position or orientation. There is no transformation needed since these values are all relative to the central anchor point mentioned previously.

To enhance collaborative analysis functions, we can also share collaborator's gaze position when they are observing shared objects. This provides information regarding to which part of visualization the collaborator is focusing on and thus user can also provide his or her insights concerning the observation. As shown in Figure 6, we have developed two levels of gaze sharing. The high level renders the accurate gaze locations from remote collaborators in real-time,



Low level sharing only highlights the state boundary



High level sharing reveals the accurate gaze location

Figure 6: Two levels of gaze sharing for different privacy needs. The gaze of local user is rendered in white color, and the gaze of remote user is in green.

and the lower level only indicates the states the collaborators are looking at by highlighting the state boundaries. When a collaborator wants to direct user's attention, they can simply look at it and the other user can follow the gaze cursor to the point of interest.

6.2 Interactive Sharing Mechanism

Sharing insights about the visualization and sensemaking process is an important aspect of collaborative analysis [31]. We provide interactive functions for users to share visualization and analysis results from their private space to other users.

The private and shared spaces are automatically determined by the types of holograms rendered at the space. Our system allows users to specify the types of holograms when they are created. Private holograms can only be seen and modified by the user who created it. They can be moved to any position with HoloLens interaction.

Private holograms can be later shared at any point via a voice command. For example, a user may start with multiple layers in their private space and apply different filters on them to understand dependencies, similar release quantities between states, affect of different weather and coastal conditions etc. After completing or during the analytics process, users can choose to share interesting insights with collaborators by simply gazing at a holographic layer and using voice command "share". This creates an extra copy of the visualization under consideration and user can keep working on their private copies.

When analyzing shared visualizations, the UI buttons reflect currently applied filters and transition back to previous filters when user(s) switch to their visualization(s) in their private spaces. To differentiate between shared and private layers, we also color the outlines of the shared copy based on the color assigned to the user(s) when they first join the system, as shown in Figure 1.

Sharing is achieved by sending all the necessary information to reproduce a hologram to the server, which then sends it to every other user in that session. Once shared, the hologram's position and rotation continuously get updated and sent to each user. All shared information is sent via Unity's message system, which uses UDP networking protocol to send packets to the server and then the server sends those to the other connected Hololenses.

6.3 History Traces for Revisiting Sensemaking Process

To further enhance the process of collaborative sensemaking, we expanded our design to facilitate distributed cognition by allowing users to revisit important interactions (leading them to the current analysis results) in the physical space [41]. Since cognitive insights are often constructed and evolved during the sensemaking process, such as when encountering a new situation to reason about or finding a dead end [5], being able to record and revisit important history traces can assist collaborators to understand, present, and discuss their reasoning process jointly.

We provide an interactive method for users to record history traces. Whenever the user finds an important intermediate stage, the user can record it by using voice command "create history". Our system automatically creates a history instance which records all information from the data, physical and user spaces that is needed to reconstruct this historical scenario, including user's position, orientation, object of focus, number of layers, data attributes involved in each layer, and custom layout of visualizations. Note that only indices of data, instead of actual data, are stored; so that the amount of information required to store and share is very small. Users can create multiple instances of history during the process of analysis and our system manages all the records based on their time stamps.

The recorded history traces can be revisit anytime. We always represent each history instance by a head avatar (takes less space than the full body avatar), which is located and oriented based on the recorded data. Users can use hand gesture to air-tap each head to reveal the historical scenario. Since the involved visualizations from all history instances may overlap extensively in the physical space and require a significant amount of resources to render, we only reconstruct the visualization from a specific history instance. Users can use the voice command "show history" and "hide history" to switch between history mode and interactive exploration mode.

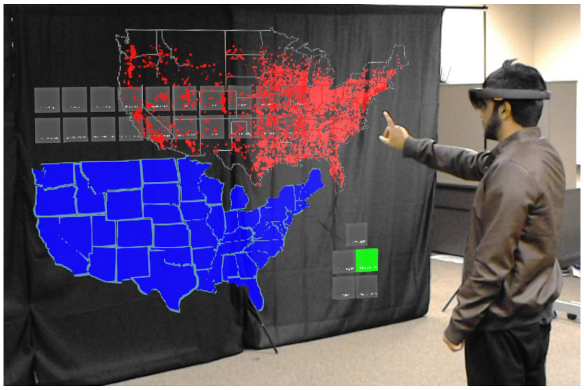
We also allow users to share their history instances with other collaborators. To differentiate between history instances of multiple users, the avatars are assigned colors for each specific user and history traces are colored by linearly interpolating the user colors and grey. By sharing these histories, user can compare visualizations, recognize joint interests and view overlapping results. As shown in Figure 7, several collaborators can share the history traces of one user and discuss the analysis process jointly.

6.4 Provenance of Interaction History

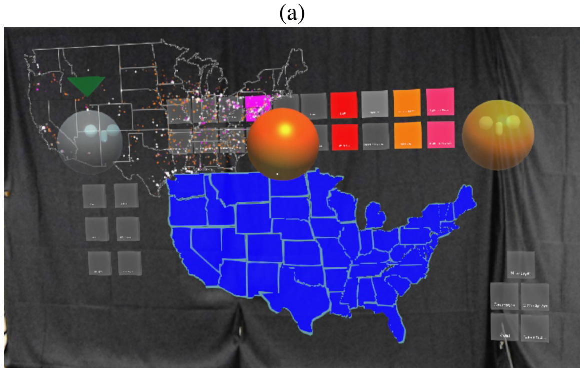
When an analyst interacts with a visual analytics system, much of that analyst's reasoning process is embedded within their interactions with the system. Thus, we provide a function of interaction provenance for the user to retrieve their analysis process.

The provenance of interaction history can be viewed as the static representation of history traces. We explore two levels of data provenance for visualizing different details of the history. The high level provenance recovers all history instances that are recorded in the system. As shown in Figure 8 (bottom), all the visualization layers recorded from all instances are shown directly. They are also represented as a list of virtual points, with color green for either generation or deletion of a visualization layer and color white for no relationships. For example, history instance 1 generated the cyan layer, while history instance 2 removed the cyan layer and added the red and green layers. The order of the virtual spheres is preassigned according to data categories of chemicals, industries, and classifications. The low level provenance method summarizes the interaction only based on the data attributes and locations. As shown in Figure 8 (top), each state shows all related history instances as virtual spheres (the same for chemical attribute and industry UI blocks). The combination of data and locations provides a quick summary of the exploration process.

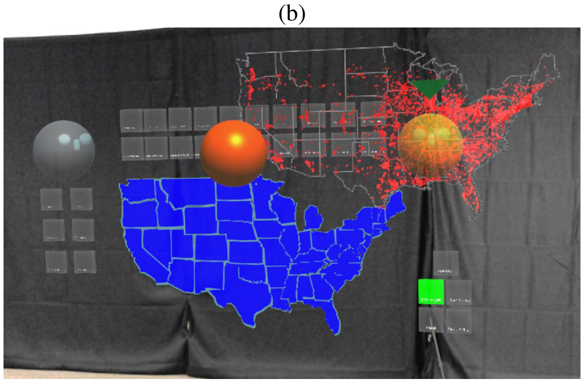
Similar to all the other holograms in our system, the interactive provenance visualization can be shared among all the collaborators. This allows better understanding and discussion of different reasoning processes.



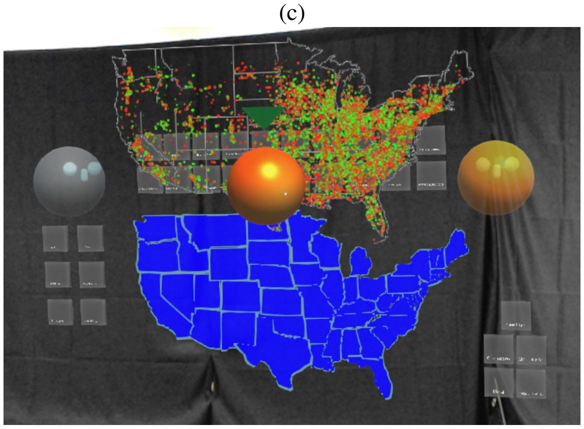
(a)



(b)

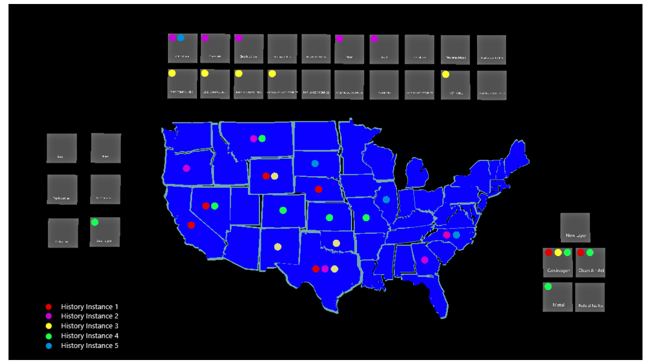


(c)

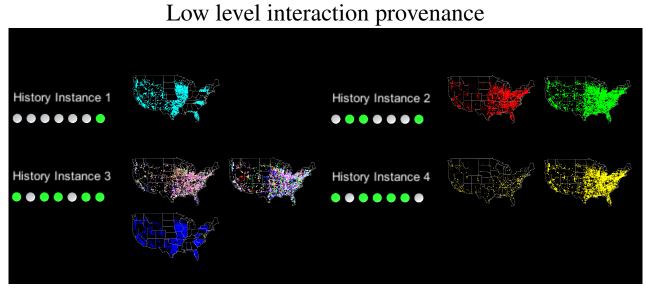


(d)

Figure 7: An example of history traces with three instances. (a) user starts analysis, achieve sub-results before saving them as history instance. (b,c,d) User revisiting each of the history instances individually by interacting with the head avatars recorded at the history time. Color intensity represent the time from the oldest (grey) to the latest (dark orange - the color assigned to the user). Re-visiting each instance reveals the visualization performed from the recorded time. The green cone icon represents history instance under current analysis.



Low level interaction provenance



High level interaction provenance

Figure 8: Example of interaction provenances taken from Unity. Subset of data being used for each history instance and the states of map being observed are recorded and shown with different colors. These two provenance examples demonstrate that user started filters, focused on specific states, continued to explore new additional filters and finally concluded with the selected ones.

7 Example Results and Usage Scenario

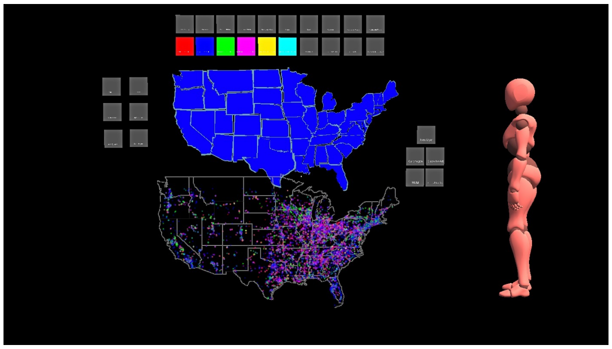
All the images in this paper are snapshots taken from HoloLens directly, except the ones marked from Unity. Some images are taken in room settings, and the others are taken in front of a black screen as a simple background.

7.1 Example Usage Scenario

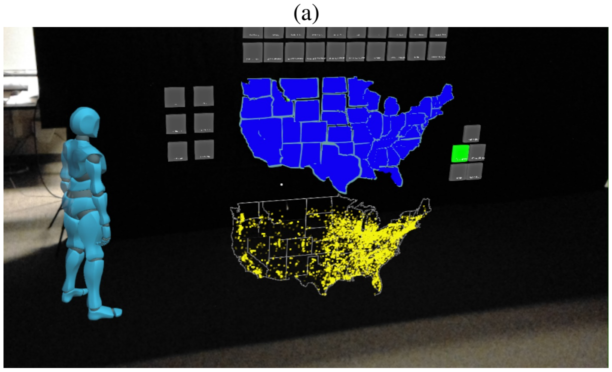
To provide a better sense of how the system works, we describe an example usage scenario below. Imagine Ross and Samantha who are majoring in environmental sciences. They want to explore the TRI dataset jointly and answer questions like 'which chemical(s) contribute most to the overall emissions?', 'which states release harmful carcinogenic chemicals' and 'how it can cause water, air and land pollution?'. They need to compare different states with comparable releases of harmful toxins.

Ross: First, focusing on most released chemicals, Ross creates a new holographic layer of the map using UI button and filters data with chemicals released in the highest amount which include *zinc, lead, nitrate, manganese, barium and arsenic compounds*, as shown using buttons in the UI. He observes that vast majority of industries releasing these chemicals are located in states of east coast and midwest region, as shown in Figure 9(a). He observes that state of Florida has the highest number of industries releasing lead compounds, while Indiana, Illinois and Ohio have industries releasing manganese and arsenic compounds. He saves these sub-results as a history trace and shares the visualization with Samantha.

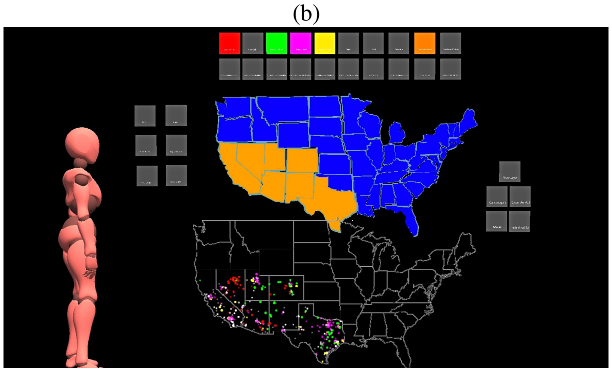
Samantha: After seeing the shared layer from Ross, Samantha is interested in comparing releases of different states and how much accumulated toxins are released in the shared layer from Ross, so she chooses to alter the heights of 3D foundation map to show the aggregated release amount of each state. She discovers an anomaly where states of Nevada, Utah and Arizona do not have large numbers



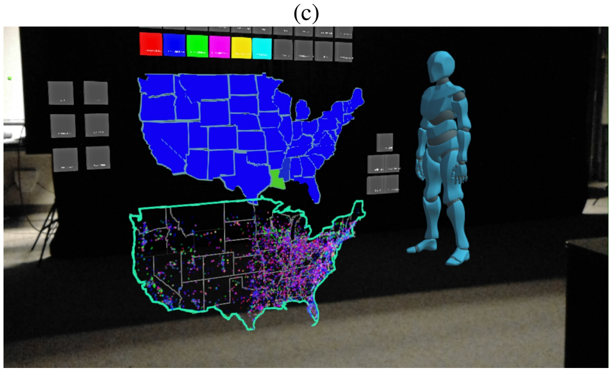
(a)



(b)



(c)



(d)

Figure 9: Snapshots taken from the example usage scenario. (a) Ross observes that industries releasing the top six chemicals are mostly located in east coast and midwest region. (b) With the shared result from Ross, Samantha observes that Nevada, Utah and Arizona have a large amount of the six chemical releases. (c) Ross continues to filter his analysis based on specific states of interest and required industry mentioned by Samantha. (d) Samantha observes that state of Texas and Louisiana are comparable in term of carcinogenic releases and their aggregated amount is more than all other states combined.

of industries releasing these chemicals but their total release amounts are still comparable to the whole east coast and midwest region, as shown in Figure 9(b). She notes down these observations and brings them to Ross's attention on the shared layer.

Ross: This anomaly intrigues him to focus on these states in his further analysis. In order to recognize the types of industries releasing such toxins, he creates another holographic layer in his private space and switches between filtering different industry types using UI buttons. He also interactively selects these specific states and discovers these states to be locations of major metal mining, fabricated metals and plastic industries as shown in Figure 9(c). He concludes these industries to be major source of such toxic releases causing air and water pollution. Again, he saves these results and also shares this new layer with Samantha.

Samantha: Concerned about the unprocessed carcinogenic releases, she creates a holographic layer in her private space to examine which states have the highest amount of carcinogenic releases. She observes a similar trend where most of these industries are spread across east coast and midwest region. She further recognizes that states of Texas and Louisiana release more carcinogenic toxins than all the other states combined, as shown in Figure 9(d). Next, she pays special attention to these states and filters specific carcinogen toxins including *lead, arsenic, formaldehyde, Ammonia and Polycyclic aromatic hydrocarbons* (PAHs). For each of these chemicals, she notes that Texas and Louisiana are quite comparable in terms of consistency and amount of toxin released. In most cases, Texas is responsible for slightly higher amount of release. Overall, these states contribute towards more than 60% of nation's carcinogen releases, and other major states include Illinois, Indiana and Michigan. She now shares these results with Ross.

Ross: From Samantha's shared results, he observes that most of these carcinogen releasing industries are located near the ocean or big lakes. This engaging observations interests him to focus on water pollution. He now wants to focus on water soluble chemicals and toxins that are harmful for human to consume. He knows that chemicals like *Dioxins* and *PolyButylene Terephthalate* (PBT) are soluble in water and can also withstand high boiling temperatures. Thus these chemicals can survive most purification methods and are extremely harmful. Important sources of these chemicals are industry of fabricated metals, electric utilities and copper industries. After appropriate filtering, he observes that states of Illinois, Texas, Kentucky, North Dakota, Montana and Washington are producing these water soluble chemicals in high quantity.

Both Ross and Samantha revisit each others and their own history instances. They also observe provenance visualization to understand which analysis result lead to motivation for further interactions. Finally, they note down all the results and observations.

7.2 System Performance

Overall, our system has achieved interactive performance for all the examples in this paper. The performance of networking is bound by the wireless network provided. Since only very little amount of shared information needs to be transferred between the server and users, there are no delay detected in the system. Our usage of particle system significantly improves the rendering performance. The rendering on the Hololens program remains above 25fps, but starts to deteriorate when we increase the number of the layers. More advanced acceleration method will be needed for larger datasets.

Since we pre-load all datasets on HoloLenses and only send a small amount of information related to collaboration interactions, the wireless network can handle the communication in real time.

8 Evaluation

Since immersive approaches for remote collaboration is still new, our evaluation focuses on exploring if our immersive approach of information sharing brings any promising benefits to applications of remote collaborative analysis.

We have performed two user studies to evaluate several factors on improving information sharing and social interaction during remote collaboration. Our main goals includes the following: (1) assess basic usability of our remote system; (2) collect qualitative feedback on several design factors of our immersive approach; (3) collect observational data on how people interact with remote system with the provided functions.

8.1 User Study 1 - Design of Information Sharing

We compare our immersive collaboration system under three conditions in terms of information sharing: (C1) No information sharing, (C2) Low-level information sharing, e.g. regions of gaze, and (C3) High-level information sharing: e.g. accurate locations of gaze.

Hypothesis. Our hypothesis is that suitable increases of information sharing can improve the performance and experience of collaborative analysis. Therefore, we expected the collaboration performance under C1 would be worse than C2 (e.g. longer time) and C2 worse than C3. We also expected that the exploration process of participants would be less affected in C1 than C2 and C2 than C3.

Participants. We recruited 8 participants, ages 22 to 28, four male and four female, with background of CS and geology. Most of the participants had some prior experience with visualization and HoloLens and were familiar with geo-spatial, but had limited knowledge of EPA TRI data.

Experimental Setup. We used two developer version HoloLenses and performed the user study for each pair of participants. For practical reason, the study was performed in a large room divided into two separate spaces, each around 3×4 meters (large enough to place holograms and work around them). Each participant in a pair took one space; where they could not see but talk to each other.

Data and Tasks. For our user study designed for around 30 minutes, we limited the dataset to include 10 chemicals of the EPA TRI data. The tasks given to each group were to explore the given dataset and answer questions collaboratively. All the questions were related to geospatial and multi-attribute dimensions, including "find the major chemical affecting USA", "find states with similar chemical distribution", and "How chemical distributions are affected by geo-locations". The same set of tasks using different chemical combinations were used in all three conditions.

Procedure. We first performed a training session for participants to get familiar with the TRI data exploration tasks. The participants were asked to create new layers and select at least two compounds such as Arsenic/Ammonia, Copper/Methanol, or Lead/Nitrate. The users were then asked to find the states with similar chemical distribution and highlight the states on the map. Once finished, the users were asked to summarize the distributions of compound chemicals according to spatial locations.

Following the training session, both participants were given a list of tasks printed on a sheet of paper. The users were asked to perform the set of tasks using the three conditions of information sharing. They were also asked specifically to work in conjunction and draw a conclusion on whether consensus was reached.

The order of the tasks was from C1 (no sharing) to C3 (highest level of sharing). We recorded videos of both participants during the study. The performances of both participants were also timed.

In the end, participants were given a post-session questionnaire to learn about their experience and encouraged to make comments about what they liked and disliked about the conditions.

Results. Figure 10 presents the performance measured in the study for the four groups. Overall, the performances of C1 are longer than C2, and C2 longer time than C3 among all groups. The standard deviations for the three conditions are 0.07162407, 0.110480524, and 0.121515707, which indicate that the performances between C1/C2 and C2/C3 are both statistically different.

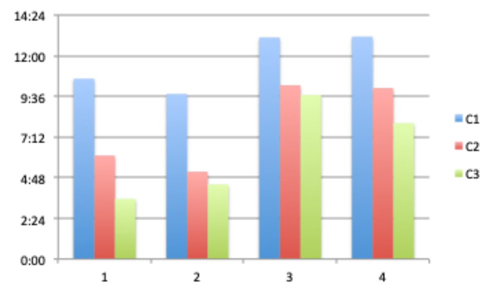


Figure 10: Duration of tasks in minutes from user study 1 showed that all four groups used less time to finish the tasks with the increasing levels of information sharing.

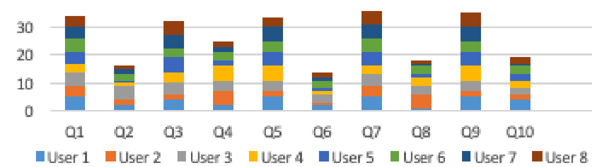


Figure 11: The SUS scores from the User study 2.

In the post-questionnaire, all users listed C3 as the most useful condition. The participants commented of the learning curve of the system as "easy understanding", as well as the collaboration experience as "I could see exactly what the other person was looking at" and "I was able to compare how other users were interacting with the layers".

8.2 User Study 2 - System Usability

Participants. We recruited a different group of 8 participants, ages 22 to 28, six male and two female, all with CS background. Most of the participants had some prior experience with visualization, but did not have much prior experience using HoloLens (two are completely new to HoloLens). Most participants were not familiar with the EPA TRI data but they were familiar with geo-spatial data.

Experimental Setup. The same as user study 1.

Data and Tasks. Similar to user study 1, we limited the dataset to include 10 chemicals of the EPA TRI data for our user study designed for around 30 minutes. We designed a set of tasks, requiring brief to extensive chemical filtering on the dataset and sharing of information among collaborators. The tasks are for exploring the given dataset and answering questions related to geospatial and multi-attribute dimensions, such as "find the chemical with the largest emissions in the states", "find 5 states with highest carcinogen releases", "explain the results using heights of states based on accumulative release amount", "create analysis history instances and re-visit them", and "share and discuss results with collaborator". Both participants needed to discuss the results and draw conclusion on whether consensus was reached.

Questionnaire. To access the usability of our remote system, we also performed the standard 10 questions SUS questionnaire [23], since it has been shown to provide both global satisfaction measurement and sub-scales of usability and learnability [54].

Procedure. Participants were given a brief introduction to the system and the dataset. Next, both participants in a study were given a list of tasks printed on a sheet of paper. The order of the tasks was from easy to difficult (based on the amount of information sharing). At the end, participants were given a post-session questionnaire to learn about their experience and encouraged to make comments about what they liked and disliked about the system and general immersive approaches.

Results. All the participants, even the ones without much experience with HoloLens, finished the tasks around 30 minutes. There were no issues with the multi-model interaction using voice, gaze, and hand gestures. All participants successfully moved around the space to analyze data from different angles during the study.

As shown in Figure 11, the average SUS score for our 8 participants was 73.25% with high of 92 and low of 55. Majority of the participants (87.5%) found the system easy to use and felt very confident while using the system. Most of them (77%) found various functions in the system well-integrated. None of them found the system to be unnecessarily complex and after brief introduction to the system and various interaction techniques, almost all of them were able to perform the tasks with minimal or no help.

8.3 Observations

From both user studies, we observed that participants agreed from each other most of the time, when visualization results were shared as the evidence. For uncertain cases, we observed more extensive physical movements as the participants walked around the holograms to observe the visualization and try to understand the conclusion from the other participant.

From our observation, all participants appreciated the functions of information sharing. They all practised sharing functions and used them during the study. When notified of new shared contents, they would actively look for the new contents and compare with their own results back and forth. Most of participants also commented about sharing as a very useful feature to communicate with each other about visualization results.

We also observed that all participants found that virtual avatar provided an interesting experience and felt strong co-presence of the other collaborator. Even though we only showed the head of remote user, participants' comments such as "there you are" or "why are you so close" clearly demonstrated the effects of co-presence.

From what we observe, users were also able to differentiate between avatars for history instances and avatar for actual collaborator and found the function to revisit interaction history very useful. They reported that it helped them understand the whole exploratory process in a better way.

In addition to our current system, voice functions can be added to allow participants to talk to each other. To our surprise, participants did not talk extensively during the study. Instead, they only talked to inform the other about something new or changes, and focused on analyzing the visualization. We think this indicates that suitable information sharing could reduce extensive communication during remote collaboration.

Participants also suggested improvements to make the system more intuitive and powerful. For example, some participants suggested to use sound feedback for indicating successful sharing and usage of interaction history. Other design options were commented as well, such as using floating menu as the interface. We plan to consider these comments to improve our system.

9 Discussions and Limitations

Remote collaboration has been explored in a variety of AR/VR settings. Different from previous work involving registration, networking, or rendering of images/objects, this paper focuses on collaborative data analysis tasks at remote sites, which are expected to become more and more useful in many visualization applications.

Our system can be improved with the following aspects. First, our approach is currently only suitable for a small group of users, as our system architecture follows the HoloLens sharing mechanism. For more users in the same collaborative scene, we will need to develop with other networking techniques. Second, for real-time collaboration tasks, robust synchronization mechanisms could be considered to ensure the system performance. Third, additional features including audio and tracking of hands can provide more communication channels for collaborators.

To suit for the diverse needs of collaboration applications, we could extend the current system to other type of collaboration and visualization settings. We will need to make several modifications to differentiate the system behaviors to remote and co-located users, such as only show avatars of remote users and still share gazes with all users. Currently, our system requires users to start from the same location, and it can be improved with better coordination method for mixed collaboration. For other types of visualization, the particle system implemented in our prototype system can suit the needs of visualization methods including scatter plot, scatter plot matrix, high-dimensional data visualization, matrix visualization, etc. We would also consider to integrate more 3D visualization methods, which take advantage of the 3D physical space surrounding users.

10 Conclusion and Future Work

This paper presents a remote collaboration system using MR for performing geo-spatial data analysis jointly. Our approach provides immersive visualization with a set of essential collaborative interaction and analysis functions that are only enabled by the latest MR technology. The goal is to enhance the effectiveness of remote collaboration through improving the awareness of each user's behaviors and reasoning process in real-time. We evaluate the effects of collaboration in our immersive remote settings and receive positive results on the aspects of information sharing and co-presence experience.

In the future, we plan to extend our approach to other types of collaboration settings, such as co-located, synchronous and asynchronous, and mixed remote and co-located collaborations. Our approach can be easily extended to asynchronous remote collaboration by storing the shared information from users. Similar approaches for co-located collaboration can be built to enhance the information sharing and collaborative analysis too. we believe that immersive approaches can bring significant benefits to collaborative visualization through new ways of information sharing and communication.

In addition, since immersive analytics is still a new field, there are many open problems for various collaborative visualization and interaction techniques that need to be studied. Existing classical visualization approaches can be integrated too, such as provenance visualization of various data and user information for summarizing the reasoning process of different users, to create more effective visualization systems for various real-life applications.

Acknowledgments

We thank for the detailed comments from our reviewers. This work was supported by the National Science Foundation under Grant Nos. 1564039, 1629913, and 1840080.

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