

XVCollab: An Immersive Analytics Tool for Asymmetric Collaboration across the Virtuality Spectrum

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ABSTRACT

Research has shown that when a group of people collaborate in decision-making scenarios, they can be more effective than when they work alone. Studies also show that in a data analytics context, using immersive technologies could make users perform better in data understanding, pattern recognition, and finding connections. In this work, we are leveraging previous knowledge in Collaborative Immersive Analytics (CIA) and Cross-virtuality Analytics (XVA) to develop an asymmetric system that enables two groups from different places on the Virtuality-Reality spectrum to simultaneously work on analyzing data. We divide users into two groups: the non-immersive desktop group and the immersive AR group. These two groups can both author and modify visualizations in their virtuality and share it with the other group when they see fit. For this, we designed a non-interruptive interface for both groups to transform a visualization from non-immersive 2D to immersive AR and vice-versa. We also provide multiple awareness cues in the system that keep either group aware of the other and their actions. We designed these features to boost user performance and ease of use in a collaborative setting and incentivize them to rely on the other group for visualization tasks that are difficult to perform on their end of the virtuality spectrum. Our limited pilot study shows that users find the system engaging, easy to use, and helpful in their data-understanding journey within the collaborative context. Going forward, we plan to conduct more rigorous studies to verify our claims and explore other research questions on this topic.

Index Terms: Human-centered computing—Visualization—Visualization application domains—Visual analytics; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality;

1 INTRODUCTION

In recent years, we have seen a surge of use-cases for big data and therefore an increase in the size and complexity of the data presented in visual analytics contexts. This has prompted researchers to look for better ways to represent such data, to assist users in making sense of it. One way to improve such representations is using immersive technologies in visual analytics systems. This is not a new idea [21], and many proposals have been made in this domain since the early nineties. The interest in using immersive technologies has been partly driven by the ability to represent multi-dimensional data in 3D, as well as the potential of better exploiting human perception capabilities and to making of embodied interaction [4, 22, 50]. This alternative is of increasing interest in many application areas, such as aeronautics, production, education, and cultural heritage [23].

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1.1 Background

In this section, we go over four of the most important domains that relate to our work. We try to provide a brief background of the concepts that we will use throughout this paper and define all relevant terms.

1.1.1 Immersive Analytics

Dwyer et al. define Immersive Analytics as the use of engaging, embodied analysis tools to support data understanding and decision making [16]. The researchers and practitioners of this field aim to support every user throughout their data journey everywhere no matter if they work individually or collaboratively [4, 23, 50]. These researchers have shown that using immersive analytics systems makes the users more effective in understanding data visualizations. Particularly, they show significant improvements in user’s sensemaking process and their grasp of abstract concepts within the data [9]. Furthermore, there are multiple studies showing that using such systems can improve a user’s performance at finding connections in the analyzed data [23, 24].

1.1.2 Cross-virtuality Analytics

As mentioned, surges in the complexity and size of the analyzed data have sparked a massive demand for more effective multidimensional data analysis. Traditional visual analytics (VA) systems have been used for years to analyze datasets with various sizes. As a result, we have VA systems that are mature and efficient in doing their task. We cannot overlook the benefits of these systems in favour of others in different dimensionalities. Knowing this fact, researchers have been looking for ways to integrate the existing traditional 2D visualizations with the concept of immersive 3D visualizations [23]. It’s important to know that immersive analytics is not here to replace traditional VA systems but to “synergize and complement” the data exploration activity [45]. In visual analytics, there is not a tool or system “to rule them all” instead, there are different tools for different situations to support users’ problem-solving strategies [38, 45].

Integrating traditional 2D systems and immersive ones show great promise in human-centred challenges such as collaborative visualization and effective interaction [30]. We discuss this integration in the context of the Reality-virtuality continuum (RVC), as defined by Milgram and Kishno [39] shown in Fig. 1. Using this definition, Frohler et al. [23] summarize this integration as “Cross-virtuality analytics (XVA)” and define it as creating “Systems for data visualization and analysis that seamlessly integrate different visual metaphors and devices along the entire RVC to support multiple users with transitional and collaborative interfaces.” This field also focuses on immersive analytics systems with interfaces that allow users to simultaneously interact in multiple modalities (AR, VR) and transition between them [26]. Researchers argue that cross-virtuality transitions could open up new possibilities for interacting with multi-dimensional data across the reality-virtuality continuum [46].

Different works refer to XVA by different names; e.g. Hybrid reality, cross-reality, and cross-virtuality analytics. When reviewing previous works, it’s important to know that all these terms refer to more or less the same subject. Throughout the other parts of

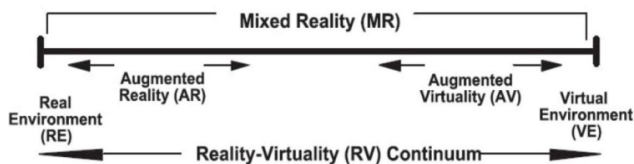


Figure 1: Milgram's Virtuality Continuum from [39] as seen in [4].

the paper (after related works), we simply refer to this subject as cross-virtuality analytics.

1.1.3 Collaborative Immersive Analytics

Research has shown that when a group of people collaborate in decision-making scenarios, they are more effective compared to when they do it alone [4, 24, 27]. In works like [47, 52], researchers show that co-located collaboration helps focus activities of work groups [47]. In some cases, this collaboration makes teams twice as productive compared to those working in a traditional environment.

In recent years, some studies have taken the idea of collaboration into the world of immersive analytics. Billingham et al. refer to this usage of collaboration in immersive technologies to enhance the visual analytics experience as "Collaborative Immersive Analytics" [4]. In this context, works like [9, 35, 36] show that teams worked more effectively when different members could see what the others were doing and could collaborate during the analysis process and decision-making. Furthermore, there is evidence that co-located synchronized collaboration improves focus on both individual and group work while raising awareness of everyone's actions. Another reported benefit of using AR/VR in co-located collaboration is that each user can have their independent view of the shared data-set, which can be customized according to their role [48].

1.1.4 Cross-dimensional Mixed-reality Collaboration

Computer Supported Cooperative Work (CSCW) [29] has been the principle guide for categorizing collaborative systems. However, as Kumaravel et al. [53] show, this model does not consider many of the novel scenarios that arise in the context of Cross-virtuality collaborative systems. For instance, "a spectator who talks to an AR user (Headset-based) who interacts with virtual objects scattered over a physical scene that the spectator cannot see" and other examples provided in [45, 53] are all not considered in traditional CSCW contexts. To remedy these shortcomings, they introduce the concept of extended space (xspace) and define it as "a space in the Milgram continuum that is perceived by a user, containing associated information of all objects, both physical and virtual, that are relevant to the collaboration task at hand." Based on their definition, they propose a modified version of the CSCW matrix that can be seen in Fig. 2.

Alongside their definition of extended space, Kumaravel et al. also define asymmetry as "being unable to see or interact with some parts of the mixed-reality environment as the other users." [53]. Per this definition, a user that is not physically co-located will be an asymmetric user, just like a user that is physically co-located but cannot access a certain part of the system. An example of such asymmetry could be a desktop user versus a VR user that work with the same data in the same system in a shared office but have access to certain features and views that the other user cannot use. A small number of studies show that using such interactive mixed-dimensional media could improve users' performance and their experience in guidance and collaboration tasks [44, 45, 53].

1.2 Challenges and opportunities

In the past three years, we have seen massive jumps in the fidelity and capability of virtual and augmented displays. Consumer-grade head-mounted displays now provide an acceptable visual fidelity,

relatively affordable price, and a good user experience. These advancements allow us to leverage the power of immersive technologies in our data analytics systems to respond to the ever-growing complexity of our analyzed data.

To summarize what we learned in the Sect. 1.1, the end goal of immersive analytics is to support data understanding and the decision-making process. We know that using immersive technologies in some scenarios makes users more effective in understanding the data, grasping abstract concepts, and finding connections within the data [9, 23]. We also know that using these technologies in a collaborative context can help boost teamwork activities, focus on tasks, and increase the awareness of other people in a group-work context [4]. There is also great potential in supporting different users and analytical roles along the RVC and allowing users from different modes of virtuality to communicate and collaborate seamlessly. [23]

In realizing the full potential of Immersive Analytics, there are some challenges. According to Churchill et al. [49], some of the most important of these challenges are 1) providing users with a shared context around the data, 2) allowing them to freely communicate with one another, also around the data context, 3) showing them role-specific viewpoints of the data, and finally, 4) keeping all of the users aware of what the others are doing in the system. Additionally, other work [8, 9] suggests that 5) providing the users with external tools for note-taking and recording their insights would be a helpful addition to any collaborative immersive analytics system.

These challenges are even more crucial as we transition into the field of collaborative cross-virtuality analytics. Especially in asymmetric scenarios where users share the same physical space but are separated by experiencing a different part of the system during collaboration [23]. For instance, the two users might be separated by their type of virtuality (e.g. desktop, VR, AR, ...) or maybe by the type of views that they can access. Thus, we posit that another important focus area is 6) collaborative information cues in asymmetric systems that let immersive and non-immersive users communicate and collaborate freely.

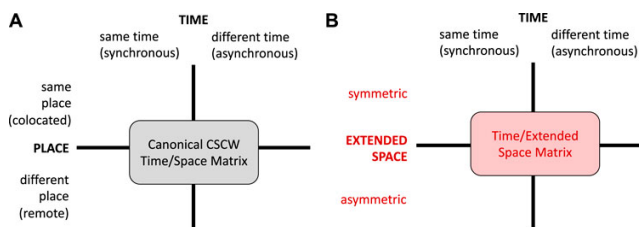


Figure 2: Comparison of the canonical CSCW matrix (A) and the extend matrix from [53]

1.3 Research Focus and goals

Guided by the existing challenges and opportunities in this field, our overarching goal is to enable analysts to more effectively understand their data, generate insights, and ultimately make decisions. Thus, we present and investigate an immersive analytics tool that lets both immersive and non-immersive groups of users synchronously work on the data while allowing them to communicate and collaborate using our system's features. For additional awareness cues, we chose AR [23] as our immersive environment and have created multiple in-system indicators that let each user know what the other person is doing in the system.

We introduce "XVCollab", a collaborative asymmetric cross-virtuality immersive analytics system for multi-variate data. We divide our users into two groups that each work on a different end of the virtuality spectrum [39]. On the one side, we have purely desktop VA users to carry out more detail-intensive analytics tasks. On the other side, we have AR users that interact with the system

through an optical see-through (OST) head-mounted display. These two groups are physically co-located and can communicate verbally or use the cross-virtuality interactions inside our system.

An important feature of our tool is that using it, these groups can interact with one another inside the system and actively observe and participate in the analysis process of the other group. We know that the systems on each side of the virtuality continuum (2D desktop systems on one side and AR immersive on the other) have inherent limitations that will force these two groups to actively collaborate for better data understanding and insight generation. [9, 24, 45]

Towards the end, we also present our methods for evaluating user performance and experience, the usability of the system, and the effectiveness of our asymmetric collaboration sub-systems. We believe that our new collaborative tool better supports communications between members of an analytics team, which can accelerate analysis and lead to additional and better insights.

2 RELATED WORK

Since our work explores the interoperability of desktop and immersive analytics in a collaborative setting, we first cover studies that propose systems with some form of interoperability between 2D and immersive modes. Then, we review works that let users collaborate in a cross-virtuality analytics setting. Finally, we explore asymmetric collaboration IA systems.

2.1 Interoperability between 2D and immersive environments

While HMDs may be convenient in performing tasks associated with spatial or multidimensional data, they can fall short in displaying statistical and abstract information. This information is instead more successfully handled by 2D visualizations [50], because typical HMDs do not offer sufficient resolution and/or are uncomfortable to wear for long periods. Understanding this, many researchers have recently explored the space of mixed-reality applications, which offer interoperability between 2D and immersive 3D environments. Almost all of these applications include features that allow their users to switch between the 2D and immersive 3D environments or use both of them concurrently. Yet, only a few of them support visualization transformations associated with transitions between the real world and the virtual one, e.g. in AR scenarios [32].

Some of the existing work focuses on showing the benefits of combining static 2D visualizations with static or dynamic 3D counterparts. Approaches such as VITA [2], aim at the collaborative aspects of the analysis process. Others target building a better understanding of the data and its underlying relationships, e.g., Wang et al. [54]. They show that using an AR extension of a PC desktop and the switch from 2D screens to an extended AR helps particle physicists to understand their data better. Gesslein et al. [25] report that users benefit from building new constructs in 3D space while still providing access to the original 2D spreadsheet layout of the data through a small tablet. Others, like the authors of PapARVis [11], demonstrate the possibilities of combining an AR authoring system with static 2D physical visualizations and report performance gains and user satisfaction in using such systems.

Others focus on demonstrating the possibilities of dynamically switching between a 2D display and a 3D immersive environment. For instance, the creators of DataSpace and Immersive Insights [9] support collaborative analysis of spatial datasets by allowing users to rapidly move between high-resolution statistical information (displayed on 2D screens) and 3D representations of high-dimensional data (visualized in AR). Their work hinted at possible advantages for using what they call “Hybrid Reality” in the sensemaking process inside an immersive analytics system, but did not provide concrete evidence for its benefits. Lee et al. [31, 33] further explored this dynamic transition. They suggest that the usage of virtual surfaces is coupled with the type of visualization used and that users often use

walls to organize 2D visualizations but use the empty space around them in VR for positioning 3D visualizations.

More recently, research has begun to explore the design space of hybrid 2D/3D immersive analytics systems. The authors of an article on the “Grand Challenges in Immersive Analytics” [18] state that there is a need for immersive analytics systems with 2D interoperability. They go further and suggest that transitions between these environments should cause meaningful transformations in data visualizations. Lee et al. [32] suggest guidelines for this novel hybrid design space and suggest that meaningful 2D/3D transformations would benefit the immersive analytics users and help them in their sensemaking process. Yet, none of these guidelines have been validated.

2.2 Co-located synchronous collaboration in cross-virtuality analytics systems

There is a growing need for synchronous collaborative teamwork in understanding complex multidimensional data in multi-disciplinary teams. Benko et al. created a system that allows collaboration between archaeologists in virtual excavations sites. Their work allowed multiple users to bring 2D models from tablets into an immersive AR world and vice-versa [2]. They further showed that the 2D/3D switch using a gesture-based system could be beneficial to the collaboration aspect of immersive excavations. However, they did not go further to explore the effects of such interactions in a data visualization scenario.

Marai et al. [37] used immersive CAVE environments and users’ portable devices in a collaborative shared analysis process. Although their work does not have any cross-virtuality component per the definition of Frohler et al. [23], the positive results of their studies inspired XVA use-cases. A good example of such inspiration is the work on DataSpace by Cavallo et al. [8]. They presented a collaborative, hybrid exploratory data-analysis system using large displays, AR representation of the data, and tabletop projections. In a comparison to a pure VR system, they identified improvements in speed and accuracy of their users’ insight generation. However, they also mentioned physical and mental fatigue as factors that can prevent prolonged sessions in the immersive environment. Reipschlagel et al. [43] expanded on this idea by creating personal spaces in a collaborative AR/large-display hybrid visualization system. They showed that this interaction concept can reduce perceptual issues in large displays for data exploration and facilitate the analysis of dense data sets. Based on their users’ feedback, they also suggested adding multiple low-level interactions (based on Munzner taxonomy [6]), such as filtering, could be beneficial for their system.

Ens et al. [20] combined a 3D model on a central tabletop display with intuitive tangible interactions, AR, and mid-air data visualization, to support casual collaborative visual analytics. They focus on accessibility and ease of use for all the parties involved. They achieved this by using tangible objects to manipulate each visualization. Using these objects, they promoted communal usage of shared controls over visualizations in a collaborative setting.

2.2.1 Asymmetric co-located synchronous collaboration

As mentioned before, in asymmetric systems at least one of the user groups are not in the same place on the virtuality spectrum as the others. Reski et al. [45] presented a hybrid immersive analytics system for two users; one in an immersive VR environment and the other using a traditional desktop web application. Their system enables real-time cross-platform (or cross-virtuality) communication between the two. They supported spatial awareness through cross-platform highlights that appear when either of the users interacts with a visualization. They also provided a mini-map that shows the location and orientation of the VR user continuously to the desktop user. Their qualitative evaluations showed that users are excited to explore scenarios in their system. Furthermore, they reported that

such cross-platform interactions create a sense of shared discovery and have great potential for group work scenarios, especially in higher educational contexts.

Kumaravel et al. [53] create three applications for mixed-dimensional media interfaces that allow the users to freely switch their “dimensionality” based on the task at hand. Their findings suggest that in such systems users perform better and have a better experience in guidance and collaborative tasks.

Most recently, Reski et al. [44] developed an immersive VR environment (with HMD and 3D gestural input) and a non-immersive desktop station (monitor, keyboard, and mouse) centred around Spatio-temporal data exploration with real-time synchronous collaborative interfaces for both desktop and VR users. The results of their study showed good usability scores, high user engagement, and balanced collaboration between the pair of users. They also showed that using this system boosts the awareness of everyone’s activities and facilitates verbal and non-verbal communications within each pair of users.

3 SYSTEM DESIGN AND IMPLEMENTATION

In this section, we present the main features of our immersive system for both the AR and our non-immersive desktop counterparts, as well as the collaborative features that connect the two users that use the system.

3.1 Initial system design goals

To create a cohesive user interface for both parts of our system, we set a series of design goals. These goals guided both our feature implementation and our study design.

3.1.1 Comparable feature set and performance between virtualities

Isenberg et al. introduced a taxonomy for different user roles in visual analytics systems [28]. Other works such as [9,45,53] showed that users move in and out of these different roles based on the scenario and necessities of the situation. They showed that this kind of role-switching has its benefits; for instance, it can make the users feel involved and engaged in the process. [44]. It can also help in experience-sharing with users from different backgrounds and levels of expertise, as sharing the experience also results in a better data-understanding performance [44].

We wanted to make sure that the users choose their visualization’s dimensionality (2D desktop vs. 3D immersive) based on the perceived performance, comfort, and properties of the active visualization. Thus, we aimed to create an immersive experience comparable to the desktop counterpart. This way, we discourage the users from treating one mode solely as a “viewer” due to a lack of features and/or performance. For instance, they should be able to construct new visualizations in both realities using a similar number of steps and with comparable ease. However, this does not mean that authoring all types of visualizations has to be equally easy or difficult on both sides. The reason is that, e.g., the immersive 3D space is a more natural fit for authoring a 3D visualization. Through this design choice, we wanted users to feel that they contribute to the work on either side of the virtuality spectrum, empowering both of them to participate in the process.

3.1.2 Seamless transition between virtualities

Cross-virtuality experiences that work on both platforms simultaneously are prone to feeling inconsistent with one-another and disconnected [32]. Any disruption of the connection might introduce gaps in a user’s interaction flow and eventually cause frustration with the system. Thus, one of our design goals was to reduce all delays or potential disruptions between the two virtualities, e.g., when transitioning content between the virtualities. We achieve this by anticipating the users’ interactions in both modes (desktop and

immersive) and pre-constructing visualizations in the background, so that transitions appear seamless. This way we can decrease the perceived latency on the users’ side, and thus make the experience smoother.

3.1.3 Cross-virtuality progress sharing

When a user transitions a visualization between the virtualities, they should feel like they are interacting with the same visualization, but only in different modes of virtuality. This means that the attributes of these visualizations should not change when transitioning between virtualities. The specific attributes that we aimed to maintain are filters, highlights, colour, and size encodings. The only case where we manipulate a visualization post-transition is when we are moving a higher-dimensional visualization to a lower-dimensional space. For instance, when we transfer a 3D scatterplot to the desktop, the third dimension of this visualization will disappear, i.e., we will not just show a projection of three-dimensional visualization on the desktop. Instead, we use different visualization channel, such as colour or size, to accommodate the third dimension in the desktop environment.

3.1.4 Synchronized cross-virtuality brushing and linking

When working with a cross-virtuality data visualization system, we want our users to perceive the system as seamless, in the sense that they are interacting with different views of the same data, regardless of which mode the data is shown in. This behaviour is consistent with previous user experiences with other visual analytics applications such as Tableau [51], which can show different 2D representations of the same data, but only on the desktop. For instance, in a cross-virtuality system the users might have a table view of some data dimensions on their desktop and a 3D scatterplot with the same data in AR. They might want to highlight a point in the table view and find its corresponding point in the 3D scatterplot. This interaction is a valid expectation for our system. It should thus support such cross-platform interactions, especially for brushing data points and linking them through appropriate highlighting.

3.1.5 Favouring desktop for detail-intensive interactions

Interactions that require detailed manipulation and/or text entry, like creating formulas, entering annotations, or manipulating tables, are easier to do on a desktop [15]. This is partly due to the inaccuracy of XR tracking and the challenges of mid-air 3D interaction, which can make accurate interactions difficult in AR/VR [1, 15]. For instance, if the users want to search for data points based on their value and highlight them in a table, this typically requires a reliable text entry and data selection input modality. Performing such actions is much easier with a mouse and keyboard on a desktop compared to mid-air hand or controller interaction.

3.1.6 Enable optional free-hand interactions

Switching between an XR controller and a mouse and keyboard can be time-consuming and frustrating. Furthermore, to most users, direct manipulation of an object in 3D space with an unencumbered hand might seem more intuitive and natural. Thus, we decided to offer support for hand-tracking-based mid-air interactions. However, using free-hand tracking without a tangible object means that giving haptic feedback is not feasible. Furthermore, in their current state, hand-tracking systems cannot compete with controllers in terms of tracking accuracy and reliability. All of these factors mean that we have to give the choice of interaction method to the user. We will evaluate this factor further in future studies.

3.2 Common Features between Immersive and Non-Immersive Sub-systems

To discuss the features of our system more easily, we divide it into two sub-systems. The immersive AR sub-system to support users in

the in the AR side of the virtuality spectrum and the non-immersive desktop subsystem for users in the “real environment (RE)” side of the virtuality spectrum.

During our design process, we first settled on the type of data that we want to show and the visualizations needed to support this data. Overall, we wanted to give the users a tool to analyze multivariate data. We also wanted to create an engaging environment that incentivizes users to explore the data and interact with the visualizations. To that end, we based our system on ImAxes [14], a data visualization system that uses an “Axis” as a data metaphor and gives the users the ability to construct and destroy visualizations on-the-fly.

One of the most important design goals for our system was to create a balance between the abilities of the desktop and the immersive system, as we want to support a natural, collaborative back-and-forth between our cross-virtuality users. Thus, we did our best to create an immersive experience that is feature-wise comparable to the desktop counterpart. Through this design choice, we wanted each user to feel capable of analyzing data, yet have them also be cognizant of the need to communicate with their peer, either directly through verbal communication or through their actions in the shared system.

3.2.1 Supported Visualization

Since our goal was not to create the ultimate visualization framework for an immersive environment, we selected only a few, representative types of multi-variate data visualizations. We thus focused on 1) 2D/3D Scatterplots , 2) Parallel Coordinate Plots (PCPs) , 3) Histograms , 4) Line graphs (trend or progress) , and 5) Scatterplot matrices . Using these visualizations, our users will have the most prevalent visualization types for analyzing multi-variate datasets.

3.2.2 Interactions

Visualization authoring and modifications: Following ImAxes [14] and multiple other studies [10, 13, 34], we wanted to enable users to create visualization using simple drag-and-drop interactions. In AR, they can simply grab two (or more) axes and place them perpendicular to one another to create a simple scatterplot or line graph (depending on the data dimension-type). On the desktop, they can similarly drag and drop data dimension names from a list and create a visualization.

Brushing and linking: Brushing and linking helps different views with partial information about the data to be linked into giving a more holistic and coherent view of the data [7]. Thus, Both systems should support brushing over visualization and highlighting the brushed data points across all the other linked visualizations, to make it easy to cross-reference data between different visualizations.

Filtering: Users should be able to filter the data based on different parameters and temporarily or permanently exclude data from their views [5]. These filters could be local, i.e., apply only to one visualization, e.g., to filter for one particular aspect during analysis, or global filters , which apply to all visualizations, e.g., to filter erroneous data or outliers. Thus, both of sub-systems at either end of the virtuality spectrum need to provide ways to filter a visualization based on one or more data dimension(s).

Color and size attribute assignment: Using color as a visualization channel can help users to distinguish between categorical attributes or to encode ordered ones [40]. Just like color, using size as a magnitude channel could be helpful in visualizing ordered data. Thus, users should be able to assign any data dimension to the colour or size channel of a visualization. This can help them visualize a larger number of dimensions and can also make pattern recognition in larger data sets easier [40].

Undo, Redo, and Action controls: It is important to give the users enough control in the system to recover from their errors. Many studies have shown that providing action controls such as undo and redo makes a system easier to use and less frustrating for users [41]. Therefore, both sub-systems in either virtuality should

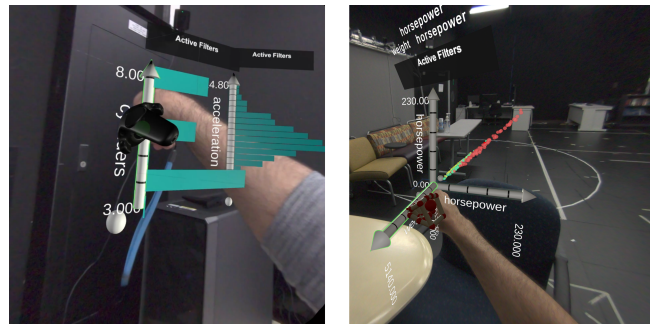


Figure 3: Supported interaction devices; Left: Tracked Controller, Right: Hand-tracking

present a robust undo/redo system that allows the users to move freely in their own activity history and recover from mistakes or unwanted behaviours.

3.3 Immersive System

As mentioned before, we based our immersive sub-system on ImAxes [14]. However, we made numerous modifications and additions to that system to suit our needs. In this section, however, we go over the design choices specific to our immersive system.

As mentioned in the 3.2.1 section, we support all of the visualization types that were supported in ImAxes. On top of those, we also added some of new visualization options, such as line and trend graphs and bar charts.

3.3.1 Interaction devices

Switching between an XR controller and a mouse and keyboard can be time-consuming and frustrating, especially if the user is not close to a desk. While one option for text entry is a portable keyboard [42], this option does not support mouse input. Thus, we decided to offer support for hand-tracking-based interactions. However, using free-hand tracking without a tangible object means that giving haptic feedback to the users is not feasible. Furthermore, in their current state, hand-tracking systems cannot compete with controllers in terms of tracking accuracy. All of these factors mean that we need to give the choice of interaction method to the user. Thus as seen in Fig. 3, users can either interact with the immersive object using a controller or their hand in our system, depending on which tracking system is available to them.

3.3.2 Moving and Authoring Visualizations

Just like ImAxes [14], our system uses a grab and place interaction metaphor to manipulate visualization elements in an augmented environment. More specifically, this interaction involves first colliding a hand or a controller with a visualization element and pinching or pulling the controller's trigger, thereby attaching the element to that hand/controller. Moving the hand/controller in space then directly manipulate the pose of that element. As seen in Fig. 4, To create new visualizations using this method, users simply grab an axis and manipulate it into different poses to create different visualizations.

3.3.3 Global and Local filtering

To achieve our goal of making an immersive system that is comparable to a desktop one, we added support for local and global filters in the immersive system, inspired by 2D work [10, 17]. Following these works, we added a filter bubble area to each of our visualizations. This filter bubble will by default show all active filters. To add new filters, we leverage users' familiarity with the drag and drop interactions; meaning they only need to simply drag a data dimension (represented by a 3D axis object) and drop it into the

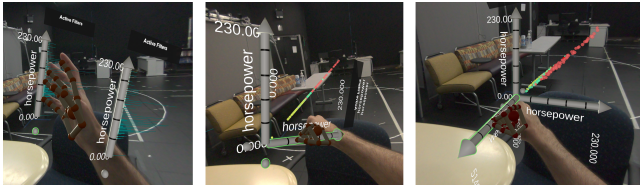


Figure 4: Authoring visualizations; Step 1) Grabbing an Axis, Step 2) Placing it Perpendicular to another axis and creation of the suitable visualization, Step 3*) Placing it Perpendicular to another visualization and creating suitable 3D visualization

filter area and the appropriate type of filter will be created based on the type of dropped data dimension. For instance, dropping an axis with categorical data in the filter area will result in a drop-down with the available options, while adding an axis with continuous data dimensions will create a range slider. You can see an example of the filtering process in Fig. 5 To enable more accurate interactions with the filters, we use hand or controller rays to adjust each filter.

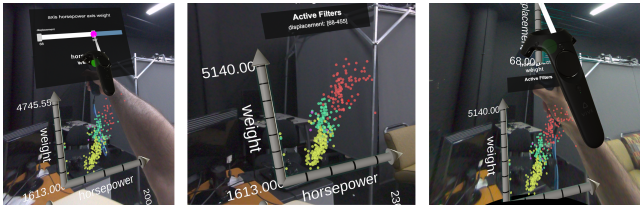


Figure 5: Steps of filtering a visualization in the immersive environment; A) Grabbing an Axis B) Releasing the axis in the filter area C) Manipulating filter using Raycast or direct manipulation

3.3.4 Undo, redo, branching visualizations, and cloning

Based on previous work [10, 55, 56] we know that sometimes users will create a visualization, and apply multiple different filters to it, or assign different data dimensions to its channels. They then might want to somehow save their current progress on this visualization while creating a different version of it [56]. Our system supports this through a combination of the history navigation (action stack) feature with a cloning feature. This way, users can *non-destructively* scroll back to previous states of the visualization and create new “branches” of that visualization by cloning it [56]. In our system, they can access the action stack by either making a “dial-back” gesture with their hands (in hand-tracking mode) or rotating the joystick (or touchpad) of their controller. To clone the currently shown state, they then use the dedicated cloning widget that is present underneath each visualization.

3.4 Non-immersive Desktop System

For the desktop system, we adapted an open-source visual analytics tool [12] and developed a plugin for it that enables the desktop system to receive commands via a Websocket interface. Furthermore, we developed a Node.js-based Websocket server that relays the messages between our immersive system in Unity and the desktop system in a web browser. This desktop system supports the creation of visualization through the same drag-and-drop method that our users use in the immersive environment.

To further support the cross-virtuality metaphor, our desktop system supports the same visualizations as the immersive environment; namely histograms, bar charts, line graphs, scatterplots, and parallel coordinate plots. It also features robust cross-virtuality brushing and filtering, which allows the users to drill down into the visualizations

and identify desired parts of the data or individual data points. Finally, this system supports a spreadsheet-like data representation that allows the users to work with the details of their data in the form of data tables.

The desktop user interacts with the system through the mouse and keyboard and sees various content on three different monitors. You can see this screen configuration in Fig. 6. 1) The monitor directly in front of them is the main monitor, and they interact with the analytics system through this display. This display is visible to the AR user but the AR user cannot directly interact with the contents of this display. In other words, the center monitor is read-only for the AR user. 2) The second monitor acts as a shared interaction monitor, which also shows the non-immersive visual analytics system. However, this display area acts as a medium between desktop and AR users. Both users can drag and drop to and from this monitor (the desktop user using the mouse and keyboard and the AR user using the virtual replica of this display in the immersive space). 3) The AR viewpoint monitor, which acts as a window from the real world into the AR world. It allows the desktop user to see the virtual 3D space as seen by the immersive user. This display does not support any interaction on either side.

3.5 Cross-virtuality and Collaborative Features

To address the challenges mentioned in Sect. 1.2, we created a set of features that help users to connect the immersive and non-immersive parts.

3.5.1 Shared context around the data

All users must be able to see and interact with the same data, as this provides them with the common ground for collaboration and communication about the analysis process [19]. Towards that end, we put virtual desktop screens in unobtrusive positions around the AR user. By looking at those screens, the immersive user can see what the desktop user is doing and interact with them, as described below. The virtual screen configuration for these displays is shown in Fig. 6.

3.5.2 Role-specific viewpoints of the data

One of our design guidelines is to favour the desktop for detail-intensive actions. With that in mind, we give the desktop users access to drill-down features on both the visualizations and also table-like spreadsheet views of the data. This enables them to create complicated filters and formulas, group data based on different attributes, and even select single data points. Still, the desktop users can only interact with 2D views of the data and cannot create 3D visualizations in their system - the only way for them to see a 3D visualization is to look at the image on the AR viewpoint monitor.

On the other hand, AR users can freely work with three-dimensional data visualizations, and move and rotate them around to look for different patterns in the data. These users have access to the filters, too. However, the filtering system on the AR side is not as powerful as the desktop system. We made this decision to simplify the interactions in the AR system and decrease the users’ cognitive load. Still, the AR user can ask the desktop user to create specific filters and then look at their representation of the desktop view.

3.5.3 Collaboration information and awareness cues

Both desktop and AR users can create a visualization in their respective systems. When a user creates a visualization at their end of the virtuality spectrum, that visualization stays there until the time that the user in that virtuality decides otherwise. If the desktop user decides that they want to share a visualization with the AR user, they highlight that visualization with a mouse click (either on the main monitor or shared monitor). Then the AR user can simply reach out and grab the highlighted visualization from the virtual representation of the desktop and take a clone of it to the 3D space. On the other

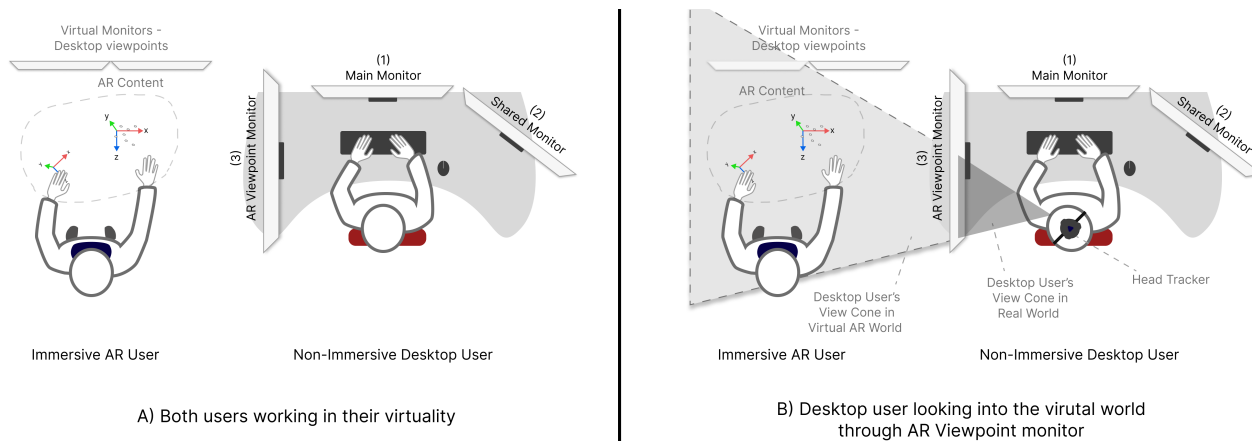


Figure 6: Screen configuration for Immersive and non-immersive users

hand, if the AR user decides to share something with the desktop user, they can push that visualization into the virtual representation of the shared monitor. Doing so results in a clone of that visualization appearing in the desktop system. These visualization clones inherit all of the filters and encodings of the original visualization. This helps in moving the work back and forth between virtualities.

Due to the presence of the virtual desktops in AR and the desktop display that shows the AR view to the desktop user, both the users are aware of what the other person is doing at the moment. The collaborative information cues such as highlighting and shared displays thus let each of the users be “in the loop”. We also use unique colours for highlighting for each user whenever they are interacting with the system so that the other user can clearly perceive the corresponding actions.

3.5.4 Contextual free communication

Since our two user groups are physically co-located, they can easily communicate verbally. Moreover, whenever a user in our system highlights the data at either end of the virtuality-reality spectrum, the same data will be highlighted in all of the visualizations throughout both the immersive and non-immersive system as mentioned in the previous section.

Furthermore, visualizations that are cloned from one virtuality to another are linked together. Any changes in filters, highlights, or ranges that apply to one linked visualization will also apply to its counterpart. This means that depending on the scenario, a user can ask another user to help them in modifying a visualization to their liking.

4 INITIAL IMPRESSIONS AND EVALUATION

Collaborative immersive analytics systems feature multiple different variables that can complicate the evaluation process. Therefore, they are mostly evaluated through field and laboratory observation studies [3]. Previous work in the collaborative immersive analytics field have shown that mixed-method studies that combine both open-ended and controlled evaluations can provide practitioners with holistic insights [4].

We hypothesize that our cross-virtuality asymmetric collaborative system improves the quality and quantity of the insights generated by the users. Previous work such as [9, 32] has hinted at this potential. We also believe that when presented with a high-dimensional data set, seamless transitions between the virtualities together with the cross-virtuality interactions (such as synchronized brushing) increases users’ involvement in a collaborative data-understanding effort. Towards that goal, we aim to investigate these hypotheses in

three different scenarios: 1) collaboration in a symmetric co-located pure desktop system, where both users use the desktop system on two different computers while sitting side by side, 2) collaboration in a symmetric co-located pure AR system, where both users will be wearing AR HMDs to analyze data, and 3) collaboration in the asymmetric co-located cross-virtuality system, where one user uses a desktop and the other one AR to analyze the data.

The choice of data is important for our evaluation. We need data that is multi-dimensional and encourages the users to create different types of visualizations in 2D and 3D with different visualization channels (e.g., colour and size). We also need a dataset that benefits from holistic views into data to find general patterns and clusters and also benefits from drill-down interactions to reveal details. This way both desktop and AR users will be motivated to engage in the process and collaborate. We also need to avoid any familiarity biases that participants might have, because they can affect the results in terms of performance. A dataset that was used in previous work [34] has all of these properties, which also yields a good baseline to compare our results with that previous work.

An initial pilot test with two subjects indicates that our hypotheses are likely valid. That said, we are planning for more rigorous evaluation to validate our observations. More specifically, we are planning to conduct a mixed-methods user study, like [33], and ask the users to complete a set of analytics tasks in the three different scenarios mentioned above. To measure performance, we will measure users’ task completion time, completion rate, number of valid insights, and error rate. We will also collect System Usability Scores (SUS) through post-task questionnaires. Qualitatively, we will record each user’s session and later extract all noticeable behavioural patterns. Finally, at the end of each session, we will conduct interviews to examine the validity of the more objective data and gather more insights into the usability of our system.

5 LIMITATIONS

Given that current HMDs are not truly suited for being used all day long, we can only simulate such a situation by providing users with a state-of-the-art AR HMD with a resolution that is close to human eye-sight. That said, we expect that our results could be affected by factors such as cyber-sickness, fatigue, and the general uncomfortable nature of wearing HMDs. To remedy some of these effects, we plan to provide users with short breaks between the tasks, where they will fill in questionnaires about their perceived tiredness.

Based on what we have learned from the most recent studies in this domain, the characteristics of the participants play an important role in their type of collaboration [4]. For instance, a user that believes in doing everything themselves, instead of asking for help

from collaborators, could be a challenge in testing our collaboration system. That said, we will try to reduce such issues by using a well-balanced dataset and tasks that require the users to use both the AR and desktop sub-systems.

Other limitations include the lack of accuracy of AR tracking systems [1]. To diminish the potential effects of this factor we set up the system in an isolated area, to ensure the system suffers from as little tracking noise as possible.

6 CONCLUSION AND FUTURE WORK

In this work, we introduced an asymmetric collaborative cross-virtuality visualization tool that enables its users to easily create visualizations at either end of the virtuality-reality spectrum, analyze the data using either an AR HMD or conventional visual analytics tools, and seamlessly communicate between the 2D desktop and immersive 3D modes. Our system provides the users with in-system modes of communicating their actions and supports the awareness of the other users' work through our collaborative awareness cues. The overall goal of our work is to understand the effect of such a system on users in terms of their sensemaking performance and their emergent behavioural patterns. Preliminary results from our pilot study hint that users find the system easy to understand, engaging, and helpful in improving their data exploration journeys.

We plan to conduct further studies to verify our initial observations. We are also interested in exploring scenarios involving remote and mixed-presence situations and comparing them with our cross-virtuality co-located system. Finally, we will later package and publish all modifications to our base visualization engines as an open-source project so that other researchers and practitioners can also benefit from our work.

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