

# HybridAxes: An Immersive Analytics Tool With Interoperability Between 2D and Immersive Reality Modes

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## ABSTRACT

Throughout the visual analytics process, users create visualizations with different dimensionalities. Research shows that in this process users benefit from being able to simultaneously see 2D and 3D modes of their data visualizations. Towards supporting this potential need, we introduce HybridAxes, an immersive visual analytics tool that allows the users to conduct their analysis at either end of the Reality-Virtuality continuum – either in 2D on desktop monitors or 3D in an immersive AR/VR environment – while enabling them to seamlessly switch between the two modes. We believe that by using our system, users will find it easier and faster to understand and analyze multi-dimensional data. An initial pilot test indicates positive trends in terms of users’ performance time and usability metrics compared to the standalone desktop or AR/VR counterparts. Our preliminary results also suggest that users experience a lower cognitive load while task-switching between these virtuality modes. This reduction in mental effort causes them to perceive the system to be unobtrusive and pleasant to work with. Going forward, we plan to conduct more rigorous studies to verify our claims and to 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 AND RELATED WORK

The idea to use immersive technologies to carry out visual data analysis tasks is not new [16] and many proposals have been made since the early nineties. Indeed, the interest of researchers in the use of immersive technologies has been driven by the ability to represent data in 3D, as well as the possibility to better exploit human perception capabilities and to make use of embodied perception and interaction [17].

In the past few years, we have seen a surge in the popularity of immersive visualization and analytics systems. Researchers have shown that immersive environments such as AR/VR systems can potentially accelerate the sense-making process [5, 24]. They have also shown that using a combination of 2D displays and 3D mixed-reality environments can be beneficial for gaining a better understanding of the data. Many researchers and practitioners have created systems to visualize and analyze data in AR/VR. These systems range from static displays of data in HMDs [5, 19, 27] to interactive systems that support real-time data and view manipulation [3, 4, 10, 14, 24, 25, 29, 33].

In this work, we present HybridAxes, an immersive analytics systems that seamlessly operates between a 2D desktop and virtual 3D space. Our goal was to create a system for future non-intrusive AR/VR displays that users can comfortably wear while working on

their desktops. In this future, the line between working on a desktop and in a AR/VR space is blurred. Using our system, users can then start their analysis with creating visualizations on-the-fly in either of the realities. Then at any time during their analysis, they can simply grab a visualization and lift it from their monitors to the 3D world, view and manipulate it and when they are done, drop it back on their monitor and continue their analysis on desktop, or vice versa. They can also highlight or filter data points in either of these realities and observe the changes in the other-virtuality counterpart visualization.

We based our system on ImAxis [10], an interactive immersive visualization tool that allows its users to rapidly create visualizations using intuitive drag-and-drop interactions in Virtual Reality. First, we expanded this system by improving its rendering performance, adding support for two other types of visualizations, adding the ability to apply local and global level filters to each visualization, adding the ability to clone a visualization with all of its filters to support branching analysis, and supporting undo and redo through an action history (stack). Then we used a video pass-through HMD to bring our system to AR and allow the users to see the real world. Video pass-through gives us the ability to show a virtual desktop instead of the real monitor, so that the users can interact directly with the desktop system through the AR system. Also, video pass-through systems do not have the contrast limitation of normal AR glasses, so reading the augmented content is easier in them. Finally, we modified an open-source web-based desktop visual analytics application, CODAP [8], to enable cross-platform operations between our immersive application in Unity and a desktop environment.

### 1.1 Related Work

While HMDs may be convenient in performing tasks associated with spatial or multidimensional data, they can fall short in displaying statistical and abstract information, which is instead more successfully handled by 2D visualizations [30], typically because they do not offer sufficient resolution and/or are uncomfortable to be worn for longer periods. Understanding this, many researchers have recently been exploring the space of mixed-reality applications that offer interoperability between 2D and immersive 3D environments [18]. Almost all of them include features that allow their users to switch between the 2D and immersive 3D environments or use both of them concurrently. Yet, only few of them support visualization transformations that happen when the users transition between the real world and the virtual one [24, 28].

Some of the existing work focuses on showing the benefits of combining static 2D visualizations with dynamic or static 3D counterparts. These benefits aim at the collaborative aspects of the analysis process, such as in VITA [3]. Or they target building a better understanding of the data and its underlying relationships, e.g., Wang et al. [34]. They show that using an AR extension of a PC desktop and the switch from 2D screens to an extended augmented reality helps particle physicists to understand the data better. Gesslein et al. [20] report that users benefit from building new constructs in 3D space while keeping the original 2D spreadsheet layout of the data in a small tablet. Others like the authors of PapARVis [7] demonstrate the possibilities of combining an AR authoring system with static 2D physical visualizations and report performance gains and user

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satisfaction in using such systems.

Other work focuses 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 [5] 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 sense-making process inside an immersive analytics system, but did not provide concrete evidence for its benefits. Lee et al. [23, 25] further explore 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.

In more recent years, research has begun to explore the design space of hybrid 2D/3D immersive analytics systems [18]. The authors of an article on the “Grand Challenges in Immersive Analytics” [13] 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. [24] 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 the sense-making process. Yet, none of these guidelines have been validated. More recent work, like [22], explored the core advantages and challenges of such transitional interfaces.

## 1.2 Motivation

Humans live in three-dimensional spaces in our real world and naturally interact with the three-dimensional objects within said space. While one can imagine interacting only with (flat) images of 3D objects in the real world (such as images printed onto sheets of paper that float in mid-air), such an impoverished environment seems very dissatisfying, especially if one is interested in the 3D nature of the objects in question. Research has provided objective evidence for the benefits of seeing a 3D virtual visualization in an actual three-dimensional space and not “just” as a 2D projection [1].

Most of the reviewed systems offer some form of interoperability between 2D and immersive environments. However, they rarely support dynamic visualization creation/modification. Thus, it is interesting to see how users perform in a system that can seamlessly operate in 2D, and AR/VR and instantly switch between these modalities/realities. Studies suggest that such a switching functionality could improve the sense-making process [5, 15] and potentially help the users to have a better overview of the data, extend their workspace, and facilitate data understanding [20, 34]. Yet, we still need to verify this claim and investigate what happens if users are able to create rapid visualizations on the fly while being able to switch between 2D and immersive modes. More specifically, we aim to answer the question “How does the ability to transition between 2D and 3D visualizations affect the interactive analysis process in IA systems?” We are interested to see the effects of such a system on users speed, rate of insight generation, error rate, and their perceived usability and satisfaction from the experience.

## 2 DESIGN GOALS

Previous work has shown that if a data visualization has more than two visible attributes, seeing those other attributes in higher-dimensional spaces could be helpful in better understanding the data [1, 5]. This fact, alongside the benefits of showing 3D virtual models in 3D space [1] informed our design goal of giving analysts the choice to switch between these dimensionalities/realities as they see fit. Some of our goals in the design of this system are as follows: 1) comparable feature set and performance between realities,

2) seamless transition between realities, 3) clear signaling of transition status, 4) synchronized cross-virtuality brushing (and linking), 5) favouring the desktop for detail-intensive visualizations, and 6) enabling free-hand interaction.

In this section we discuss each of these design goals in detail. The following section discusses their implementation.

### 2.1 Comparable feature set and performance between realities

We wanted to make sure that the users choose the mode of work (desktop vs. immersive) based on the perceived performance, comfort, and properties of the active visualization. Thus, we did our best to create an immersive experience that is comparable to the desktop counterpart. This way there is less motivation for the users to abandon one mode due to a lack of features and/or performance. For instance they should be able to construct new visualizations in both of the realities in a similar number of steps and with comparable ease. This does not mean that authoring all types of visualizations need to have the same level of difficulty in all realities. 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 can continue most of their work in either side of the Reality-Virtuality continuum, giving them the ultimate choice.

### 2.2 Seamless transition between realities

Cross-virtuality experiences that need to work on both platforms simultaneously are prone to feeling inconsistent with one-another and disconnected [24]. Any disruption of the connection might introduce gaps in the user’s flow and eventually cause frustrations with the system. Thus, one of our design goals is to reduce all delays or potential disruptions between the two realities. We achieve this by anticipating the users’ interactions in both modes and pre-constructing visualizations in the background. This way we can decrease the perceived latency on the users’ side, and thus make the experience smoother.

### 2.3 Clear signaling of transition status

Clear “visibility of system status” is a characteristic of good user interfaces [26]. Consequently, we need to ensure that when the users begin a transition between the realities, the system provides them with ample feedback. This feedback will let them be aware of their action and if needed, revert the action. It can also reduce users’ frustration with the system since they know what has happened is due to their action. Towards that goal, we designed standard ways of signaling the beginning and end of a transition (either from immersive to desktop or vice versa) through visual and haptic feedback. Our design is also compatible with the design space guidelines that were put forward in the “grand challenges” for immersive analytics [13].

### 2.4 Cross-virtuality progress sharing

When a user transitions a visualization between the realities, they should feel like they are interacting with the same visualization, but only in different realities. This means that the attributes of these visualizations should not change when transitioning between realities. The specific attributes that we want to keep the same are: filters, highlights, color, and size. 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 channels such as color or size to accommodate the third dimension in the desktop environment.

## 2.5 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 in which virtuality the data are shown. This is consistent with previous user experiences with other visual analytics applications such as Tableau [31]. For instance, the users might have a table view of some data dimensions on their desktop and a 3D scatterplot that represents the same data in AR. They might want to highlight a point on the table view and find its corresponding point in the 3D scatterplot. This is a valid expectation and our system should support such cross-platform interactions, especially for brushing data points and linking them through appropriate highlighting.

## 2.6 Favouring desktop for detail-intensive interactions

Interactions that require detailed manipulation and/or text entry, like creating formulas or manipulating tables, have been shown to be easier to do on a desktop [11]. This is partly due to the inherent inaccuracy of AR/VR tracking which can make accurate interactions difficult in AR/VR [2, 11]. For instance if the users want to search for some data points based on their value and highlight them on a table, they would require a robust typing and selection system, something that is much easier to do with a mouse and keyboard on a desktop compared to mid-air hand or controller interaction.

## 2.7 Enabling free-hand interactions

Switching between a AR/VR controller and a mouse and keyboard can be time-consuming and frustrating. Furthermore, to most users, direct manipulation of an object in the 3D space with an unencumbered hand might seem more intuitive and natural. Thus, we decided to offer support for free-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 its 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. We will evaluate this factor further in our future studies.

## 3 IMPLEMENTATION

In this section, we will describe the implementation of our system in more detail and show how we meet the goals established in the previous section. As hardware platform we used a Varjo XR-3 head-mounted display with four Lighthouse 2 tracking beacons and a Windows PC with an Intel i7 CPU and a Nvidia RTX 3080Ti GPU.

### 3.1 Core Immersive system

We use ImAxis [10] and IATK [9] as our base visualization engine, as both are available as open-source Unity [32] packages. We made several modifications to create our desired immersive analytics tool and discuss the most important of these here.

#### 3.1.1 Improving rendering performance

To show hundreds of thousands of data points at the same time, we added support for leveraging the power of graphical shaders, which greatly improves the rendering performance. To achieve this goal, we expanded on the optimization techniques that were already (partly) offered by IATK. These techniques enable us to move the burden for the visualization creation and modification to the GPU, instead of the CPU which drastically improved the speed and rendering stability of our system.

#### 3.1.2 Adding Support for local and global filters

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, e.g., [6, 12]. Following this work, 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 3D axis object) and drop it into the 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. To enable more accurate interactions with the filters, we use hand or controller rays to adjust each filter.

#### 3.1.3 Undo, redo, branching visualizations, and cloning

Based on previous works [6, 35] we know that sometimes users will create a visualization, 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 an alternate version of it [35]. 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 a visualization and make new branches of that visualization by cloning it [35]. In our system, they can use 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 button that is present underneath each visualization.

## 3.2 Core desktop system

For the desktop system, we adapted an open-source visual analytics tool [8] 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 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 brushing and filtering, which allows the users to drill down in the visualizations and to identify desired 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.

## 3.3 Hybrid system and interactions

Using the Websocket server, we enabled our immersive and desktop system to communicate with each other. There are three types of interactions between the real-world desktop system and the Immersive AR/VR one. The first one is the ability to lift a visualization from the desktop, either by using their free hand (tracked with the Ultraleap hand-tracking system embedded in the Varjo XR-3) or a controller and then see it manifest in the 3D immersive space. The second one is to "push" something from the 3D immersive space back to the 2D desktop. Doing this causes the immersive version to "vanish" into the desktop and the 2D representation of that visualization to be created on the desktop application. The transition from desktop to AR and vice versa is visible in more detail in Fig. 1 and Fig. 2. The third one is the ability to brush a specific data point on either side of the Reality-Virtuality continuum (either on desktop or in immersive AR/VR) and see its other-virtuality counterpart highlighted as well.

#### 3.3.1 Optimizations to increase the perceived fluidity

We took several measures to make the users feel the system is working as smooth as possible. Three of the main ways are 1) predicting

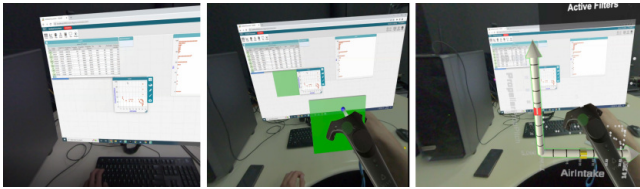


Figure 1: The process of “pulling” a data dimension away from 2D monitor panel. From left to right: 1) before extrusion, 2) grabbing of the visualization representation, and 3) releasing the intermediary representation and the creation of its 3D counterpart.



Figure 2: The process of “pushing” a visualization into a 2D monitor panel. From left to right: 1) before pushing the Axis into the panel, 2) colliding the Axis with the virtual representation of the monitor and seeing the release prompt, and 3) releasing the Axis and the creation of a visualization on the desktop side.

controller/hand coordinates on the monitor, 2) pre-constructing visualizations before cross-virtuality transitions 3) communicating the potential “active” visualization by sending WebSocket messages.

To anticipate the 2D position that the 3D controller might intersect with on the (virtual collision detectors of the) desktop monitor(s), we use an invisible ray that emanates from the controller in the direction of its movement towards the monitor. Using that ray, we find the corresponding  $(x, y)$  coordinates on the desktop. If the controller is closer than a certain distance to the monitor, we start communicating this desktop position to our web-based plugin, which in turn makes CODAP API calls to identify the active visualization that is at those coordinates. We communicate the characteristics of that visualization back to Unity. Upon hitting the monitor and initiating a grab action, we pre-construct a visualization using the received information. After that and when the user starts moving away from the monitor, we show a silhouette of this 3D visualization to indicate to the user that they are doing an extrusion action. After a distance threshold, the silhouette will fade out and turn into the appropriate visualization, the one that we pre-constructed before. Doing this means that we do not incur the overhead of multiple API calls at the point of contact with the monitor, which improves the perceived latency on the users’ side.

#### 4 INITIAL IMPRESSIONS AND EVALUATION

As mentioned above, we hypothesize that enabling visual analytics users to quickly move between a 2D real world desktop and 3D immersive environment in AR/VR could improve the quality and quantity of their generated insights. Previous work such as [5, 24] have hinted at this. We also believe that when presented with a high dimensional data set, seamless transitions between these realities alongside the cross-virtuality interactions (such as synchronised brushing) could increase a user’s analysis speed and decrease their error rate compared to a traditional desktop visualization system or a purely AR/VR experience, as this will decrease the mental load for switching between realities. Still, there will likely be some cognitive overhead for context-switching between AR/VR and desktop, but we expect this overhead to be remedied by the gain in performance from seeing multi-dimensional visualizations in 3D, when moving to 3D, or more precise interactions, when moving to 2D.

An initial pilot test with four subjects indicates that both of these

hypotheses are likely valid. In this limited pilot test, we presented our participants with the open-source data collected for Melbourne housing auctions that was previously used in previous work [25]. To be able to compare our results with that work, we also presented our users with the same tasks that this work used [25]. These tasks were designed by the original authors of that paper to ensure that the participants will make use of the higher-dimensional visualization options (e.g. 3D scatterplots). Each user analyzed the data in three different scenarios: 1) Just using the desktop system 2) Just using the AR system 3) Using our hybrid system. We measured user’s performance by measuring the time it takes for them to generate an insight and complete a task. As for measuring the cognitive load, we observed their actions and asked them to use the think-aloud method when working with the system. We also presented them with a NASA TLX questionnaire at the end of each session to further measure their mental and physical task load.

That said, we are planning for more rigorous studies to validate our observations more rigorously. More specifically, we are planning to conduct a mixed-methods user study, like the one in [25], and ask the users to complete a set of analytics tasks in three different conditions; standalone desktop, standalone AR/VR, and our hybrid system. To measure performance metrics, we will measure users’ task completion time, completion rate, number of valid insights, and their error rate as quantitative measures. We will also collect System Usability Scores (SUS) in the form of post-task questionnaires. Qualitatively, we will observe each user’s session to extract any noticeable behavioural patterns. Finally, at the end of each session, we will conduct interviews to examine the validity of our data and gather more insights about the usability of our system.

#### 5 LIMITATIONS

The future is not here yet, so the hypothetical non-intrusive head-mounted display that users could wear all day long does not truly exist, yet. Therefore we can only simulate such a situation by providing them 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, mid-air hand interaction fatigue, and the generally uncomfortable nature of wearing bulky HMDs [21]. 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.

The other limitation that can possibly sway the users into favouring the desktop system is the general noise and jitter of the tracking systems [2]. 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 HybridAxes, a cross-virtuality visualization tool that allows its users to easily create visualizations at either ends of the Reality-Virtuality continuum, analyze the data using conventional visual analytics tools, and seamlessly transition between the 2D desktop and 3D immersive modes. Our goal is to understand the effect of such a system on users in terms of their sense-making performance and their emergent behavioural patterns. Preliminary results from our pilot study hint that users find their performance in our hybrid system comparable to standalone desktop counterparts and better than a standalone AR/VR system.

We plan to conduct further studies to verify our initial observations. We are also interested in exploring a scenario in which two users collaborate in an asymmetric XR-Desktop combination. 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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