

**Everyday Scientific Visualization: Making 3D  
Visualization Techniques Accessible for Day-To-Day  
Team-Science Collaboration and Analysis**

**A DISSERTATION  
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL  
OF THE UNIVERSITY OF MINNESOTA  
BY**

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**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF  
Doctor of Philosophy in Science**

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**June, 2022**

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# Acknowledgements

My greatest strength is my luck with people. In every facet of my life, especially during uncertain times, there always have been people who provided support, guidance, and opportunities. My luck persisted through my years as a Ph.D student. This work wouldn't have been possible without the help from these people.

First or foremost, I thank my advisor Dan Keefe for inviting me to work at his lab, which has been a joy and an honor working in an environment that encourages diversity, collaboration, and friendship. With his guidance and commitments to his students, I was able to slowly improve skills and confidence for conducting research, presenting works, and collaborating with others. I thank him for patience and trust as these help me challenge myself to tackle difficult problems and instill a drive for constant improvements.

I thank Tobias Isenberg for the opportunity to work with him at Inria. The work I did there became the important piece of this dissertation. When working with him, I know I can rely on him for providing clear instructions and guidelines which helped me understand research and writing processes. Also I thank him for treating me like his own student, being available for questions and providing genuine care.

I thank professors Lana Yarosh and Evan Suma Rosenberg, two other committee members, for providing guidance. I thank professor Yarosh also for introducing various prototyping methods and inviting me to weekly meet-ups for hands-on experience. I would like to thank professor Rosenberg also for letting me sit in his 3DUI seminar course, which increased my research interest even more. Additionally, I thank professor Victoria Interrante for her inspiring classes on Virtual Reality and professor Stephen Guy for encouragement and career advice. To professor John Carlis, I am lucky that I attended your workshop on dissertation writing as your approach helped me write this.

I am privileged to have had the opportunity to work with amazing collaborators, some of whom are co-authors of the presented work. First, I thank researchers at the U.S. Forest Service, Charles H. Perry and Barry T. Wilson, for collaborating on several VR-based forestry visualizations. Also I am thankful for the students at the time of collaborating, Krista McCullough, Joshua Tveite, Maria Molina Espinosa, and Ninad Sinha for their assistance with implementation and design. Second, I am grateful for the opportunity of working with a cross-disciplinary team of professors, scientists, designers, and engineers for developing VR-based pain interventions. I thank Alex Haley, Anna Taberko, Ben Lifson, Francis Keefe, Gert Bronfort, Haiwei Ma, Lana Yarosh, Joseph Jolton, Linda Hanson, and Roni Evans for the opportunity. Third, to Francesca Samsel, Gregory Abram, and Stephanie Zeller at the Texas Advanced Computing Center, I owe a debt of gratitude for technical support and testing tools described in this dissertation. Fourth, creative explorations of 3DUI and visualization techniques in medical settings were possible with help from researchers and staff at the Earl E. Bakken Medical Devices Center, particularly professor Arthur Erdman and Benthany Juhnke, and at the Center of Magnetic Resonance Research, particularly professor Christopher Langlet and Hamza Farooq.

To my fellow lab mates, Seth, Dan O., Volcano, and Bridger, it has been a joy to share deadlines, conference trips, jokes, meals, Marvel's movies, and random adventures. You all made my work as your work. I am lucky that I had you all around me during the study. To Liam, Nikki, Daniel O., Devin, Sam, and Sarit, whenever I was heading to the campus, even on weekends, it was great knowing one of you will be in 2-203. Thanks for keeping me company and for teas, lunches, jokes, and so many other things. To Sean, Morgan, Kiet, Anang, Jason, Alex, Max, Ray, Angie, Zahara, Cheyenne, Amber, Matthias, Zak, and David, I thank you for assistance with the last paper and discussions during our weekly meetings.

To fellow Ph.D. students from other labs, Sarah MacRoberts, Matt Overby, Moses Adeagbo, Jeong-seok Hong, Tae-jun Byun, Jae-Shin Yoon, and Jang-yoon Kim, I am lucky that I had you all as mates to share ups and downs during the study and to call for sharing pizzas, coffees, and climbing. To senior Ph.D. students, Kate Schroeder, Bret Jackson, Seong-min Kim, Kwang-sung Oh, Kyu-sung Park, Sun-mo Kim, and Kyu-baik Choi, thanks for helping me adjust to the program and for inspiration.

Also, I want thank the people I met during my internship at Aviz: Jean-Daniel Fekete, Tobias Isenberg, Petra Isenberg, Pierre Dragicevic, Tanja Blascheck, Lonni Besançon, Paola Valdivia, Sarkis Halladjian, Xiyao Wang, and Mina Alipour. Not only the work I did there became the final piece in my dissertation, but also you all gave a priceless gift of genuine memories of being part of a community of multi-national researchers collectively advancing the field of data visualization and of companionship. Thanks for inviting me to homes, adventures, dinners, and drinks during my stay in France.

There are also other people who made tremendous impacts on my decisions to start the program and study computer science. To Dr. Gregory Metzger at the Center of Magnetic Resonance Research, I am thankful for the research opportunity and an assistantship through the Master's program. I also thank you for stories, advice at D'Amico & Sons Café, which helped me broaden my perspectives on research and life in general. Also to Benjamin Fossen, Chaitanya Kalavagunta, and Ethan Leng, it was a great joy to share an office. During my stay in South Korea, I had a great opportunity to work at the Korea Culture and Technology Institute. I thank professor Moon-gu Jeon for career advice and chances to work on interesting projects. Likewise, I also thank professor Gwang-woo Nam at Kunsan National University for genuine care for my career and well-being. Lastly, I thank Sang-gu Lee and Yoo-la Lee at GeoSung academy for letting me sit in their Photoshop, Flash, and programming classes, which taught me a joy of solving problems and programming when I was a kid.

On the non-academic side, there are families and friends who invited me to be part of their families, which helped me get adjusted to new places and provided moral support during the study. I thank my host-family the Brandows — Doug, Gail, Jonah, and Jesse — for showing kindness, generosity, and love. I cannot imagine how my experience in the U.S. would have turned out if I haven't met you all. I thank Ryan, Dr., and Mrs Thurmer for the time in Seattle over a winter break. To Dan O. and his wife Sonja, thanks for treating me like your son and inviting me to dinners, parties, and homes for holidays. Also I thank my old roommates or friends I met during the study, Ki-ho Park, Scott Brea, Hyun-woo, Dae-yeop, Colin, Mark, Derek, Aaron, and Rodney for humor and support. Lastly, I thank residents at Robert Garric in Cité for their acceptance during my stay in Paris.

Finally, I want to thank my parents, grandparents, and my sister for their unconditional supports and love — a bedrock of happiness and sources of inspiration to continue exploring, practice friendship & comradery, and be excited about whatever comes next.

## Abstract

This dissertation aims to make scientific visualizations accessible for day-to-day operation of team-science. Building upon previous work that support visualization tasks in a wide range of devices and context but focus on non-spatial and spatial 2D visualizations, we introduce techniques, mechanisms, and frameworks that make visualizations of spatial 3D datasets accessible for immersive data analytics, education, and collaboration.

In the first research direction, we focus on providing engaging approaches for the public to explore high-end scientific data and introduce a VR-based visualization technique not only for immersive exploration but also for comparison-based exploration and presentation. The approach extends Portal and WIM techniques to create a unifying metaphor for comparative immersive visualization. Within the application to comparing plots from the US Forest Service’s Forest Inventory and Analysis dataset, the technique was successfully used to confirm known and discover new trends in the data.

In the second research direction, we explore new widely accessible, low-cost VR displays for data visualization and introduce the first example of a 2D + 3D VR linked view visualization on a mobile device. Showing plots in the forestry dataset, the visualization provide limited exploration capabilities, compared to our first visualization, but it provide users more accessible forms for education and training.

In the last direction, we focus on supporting collaboration across these visualization approaches—1) high-end but with computation requirements and 2) lightweight but with limited flexibility—and introduce a framework facilitating multi-person correspondence about spatial datasets for team-science collaboration. By integrating storytelling metaphor with support for spatial annotations, the framework enables users to present findings with data stories made of visuals from exploratory spatial 3D visualizations. With a flexible export of visualization results, the data stories are distributed to complementary client applications and plugins that enable different styles of story co-authorings for discussion of spatial 3D analysis. We report on user feedback and lessons learned from a deployment within a team-science context where it was used as a cross-disciplinary communication tool for visual analysis of the Antarctic ice sheets.

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# Chapter 1

## Introduction

A pioneer in computer science Jim Gray describes the twenty-first century as the dawn of a new era where new discoveries are powered by advanced computing technologies that help scientists explore massive datasets [44]. According to him, data visualization is a crucial component of these advanced technologies, and its impact on various scientific fields will continuously increase as researchers deal with bigger and more complex datasets. In fact, spatial 3D data visualizations have become essential tools for enabling breakthroughs in medicine, science, engineering, the humanities, and more (e.g., [61, 10, 120, 1]).

However, one of the key challenges is to get more and a diverse set of people involved in analysis tasks. Collaboration and communication are essential parts to science. Scientists today work in teams where it is essential to be able to communicate about their data, often across disciplines. However, visualization applications are typically designed for expert users at work. Inability to bring these visualizations outside of a current work environment can hinder us from including citizen scientists and other collaborators in a data analysis task.

One strategy for addressing this problem is to port the same type of exploratory visualization scientists use on their current high-end visualization systems (e.g., advanced volume rendering algorithms) to the commodity devices that people use regularly, for example, through remote visualization [77] or graphics shaders adapted to work on lower-power devices. Exciting research is being done in this space and, as networking

and computing hardware improve, these approaches are increasingly practical. A fundamental limitation, however, is that, as hardware improves, scientists ask even more complex questions or demand more detail, requiring ever more complex data storage, processing, and visualization to address. We are thus always likely to see some disconnect between the high-end visualization tools scientists use and the commodity devices we have in our offices, homes, or pockets.

## 1.1 Broadening the Scope of Data Visualization

In light of this situation, we take a different, complementary approach. We argue that bringing full-fledged data exploration capabilities to every devices may not be the best way to address the problem of high-end collaborative visualization for spatial 3D data, but we should rather focus on unique styles of visualization tasks each device can facilitate and connecting users using these devices with support for sharing visualization results and their findings.

In the information visualization field, which often deals with abstract 2D data, researchers have been investigating ways of enabling visualization tasks in new display technologies [71, 11, 51], including people from diverse backgrounds in analysis tasks [43, 42, 114], and supporting communication and collaboration [42, 69, 7]. For instance, by having data visualizations in devices and media formats that we see on a daily basis, users can look at data visualizations while walking on the street [11] or even receive these in their mailbox [79]. Also by using exploratory data visualizations to the Web, online users analyze data uploaded by other users [114], and the users can collaborate and discuss about presented data by annotating and leaving comments directly on the visualizations [42].

In the scientific visualization field, which frequently deal with spatial 3D data, researchers also have been investigating ways of bringing visualizations to the outside of a work environment, for instance, by developing storytelling techniques to present scientific data [119, 108, 78] and public-facing installations for museums [82, 56, 123]. However, there are fewer options for different devices scientists can employ in their analysis tasks and people they can include for collaboration. Also, we can only reach audiences at specific locations, and there are no means for the audience to provide



feedback, which might be an acceptable approach for public-installations but not for team-science projects.

## 1.2 Everyday Scientific Visualization

In this dissertation, we fill these gaps in the scientific visualization research and introduce visualization techniques, applications, and frameworks that grant us access to visualizations in our day-to-day operations. We call these Everyday Scientific Visualization, and this has **three research components** that set it apart from traditional expert-driven, desktop-based data analysis tools.

1. **Everyday People:** In addition to data visualization applications designed for expert users, we believe that there could also be various visual analytic tools for lay and novice users. The main purpose of using these tools would not necessarily be for fostering new scientific discoveries but for gaining insights at a personal level, e.g., analyzing personal datasets, communicating data-driven stories to friends and families, or learning about already well-established scientific knowledge.
2. **Everyday Devices:** In addition to high-end devices such as super computers, we believe that visualization could be made available in low-cost devices like mobile phones that people carry around and use in daily activities. In addition to traditional devices such as desktops, new display devices could facilitate new ways for experts to explore their datasets.
3. **Everyday Communications:** In addition to collaborating with onsite people, we believe that insights and findings obtained from visualization applications could also be shared with the people at different places and times. Authoring features such as creating a visual content for conveying data-driven stories become common in any exploratory application, and these visual artifacts are written in a format that can be easily shared in other communication platforms such as emails and social media sites.

Broadening the scope of scientific visualizations will give us these **advantages** in conducting a team-science project. Scientists can use data visualizations not only to

analyze their data but also to present their work and teach students, and they can show their data in accessible and engaging ways by taking advantage of unique styles of visualization tasks supported by different devices. Additionally, people from various backgrounds and with skill sets, e.g., citizen scientists and designers, can bring new expertise to the team and provide new angles to solving a problem.

However, traditional scientific visualizations are typically designed as high-end desktop-based, expert-driven data analysis tools. When we deploy existing scientific visualizations in these contexts, we start to face these **obstacles**.

- O1. Using scientific visualizations often requires domain expertise and visualization literacy, which makes it difficult for lay and novice users to use the visualizations.
- O2. Most scientific visualization software require high computing power. Therefore, it is difficult to run these in low-cost devices, such as mobile phones or personal laptops, that the public have access to.
- O3. Most visualizations focus solely on supporting analysis tasks; these do not have built-in mechanisms for communication and collaboration.

Our key approach to overcoming these obstacles is improving *human-to-human communication* about the data so that scientists can better share their work with general audience and can have dialogues with others who might have different skill-sets and backgrounds. The approach is specified into **three research directions**. The **first** research direction focuses on providing engaging approaches for the public to explore high-end scientific data. Specifically, it uses high-end display technologies that scientists often use for data analysis for showcasing scientific data to the public in a way that enables immersive and engaging data exploration. At the same time, we develop visualization and interaction techniques that enable fundamental data analytic and presentation tasks that are not currently supported in these visualization approaches (O1). The **second** direction enables common visualization practices in low-cost devices that the public have access to. Specifically, it involves in developing public-facing applications where users can explore scientific data at home or in a classroom (O2).

As we work on these two research directions, people will have a diverse set of options to work with scientific data, with high-end to low-cost devices, traditional workstations

to immersive displays, and expert-driven to public-facing applications. However, the concept of Everyday Visualization is not only about having more options to look at scientific data but also about connecting users using these different options via communication and collaboration. Therefore, the last and **third** research direction focuses on *Every Communications* component that involves in developing mechanisms for creating and sharing messages to talk about findings and insights gained from analyzing spatial 3D data (O3). To encompass the work from the previous two research directions, this third research direction also focuses on developing frameworks and message protocols that enable group communication using different types of devices where users can view, interact, or even provide feedback with devices that are available at the moment or suitable for their current tasks (O1, O2, O3).

### 1.3 Key Contributions

We introduce techniques, systems, and frameworks resulting from ensuing the research directions, which are our key contributions of this dissertation.

- Several example works demonstrating Everyday Scientific Visualizations turns science communication from rare special activities to everyday occurrences
- A VR-based visualization and user interaction technique enabling scientists to share their data with the public with support for comparison-based exploration and presentation (from R1 addressing O1)
- A public-facing application enabling common visualization practices in low-cost devices (from R2 addressing O2)
- A novel collaborative visualization framework enabling improved multi-person correspondence about spatial 3D datasets in a team-science project (from R3 addressing O1,O2,O3)

### 1.4 Thesis Statement

The central thesis behind Everyday Scientific Visualization is thus:

*Making communication the number one design goal for spatial 3D visualization leads to new engaging, accessible, and collaborative tools that can shift scientific visualization from a rare, special activity to an everyday tool for data analysis and communication.*

## 1.5 Overview of this Dissertation

In this dissertation, relevant related work is presented in Chapter 2 and future work is presented in Chapter 6. More in-depth related work and future work may be found in Chapters 3, 4, and 5.

- **Chapter 3** introduces an approach that scientists can employ for sharing their high-end data to the general public. Specifically, we work on visualization and interaction techniques that support immersive exploration and a viewing of multiple data-driven virtual worlds to facilitate visual comparisons.
- **Chapter 4** introduces an approach that enable common visualization practices in low-cost devices that the public have access to. Specifically, we work on lightweight applications for mobile and tablet devices that enable linked-view and immersive visualization techniques for personal usages and educational purposes.
- **Chapter 5** introduces frameworks that support asynchronous communications around 3D visualization. Our work will be focusing on designing a message protocol and framework to connect these visualization approaches as one infrastructure for collaboration.

## Chapter 2

# Related Work

### 2.1 Employing Current Technologies for Scientific Data Analysis and Exploration

Researchers have been investigating ways of enabling visualization tasks with various display technologies. For instance, by integrating large displays with multi-touch interactions, visualization techniques facilitate interactive exploration of cosmology data [124] and in a public setting where users work together and learn about presented data [123]. Or by integrating haptic display devices or tangible inputs, users can make more precise manipulations [50] and perform better at doing certain visualization tasks [123]. And one of technologies that is gaining much attention is VR. Recent advances in low-cost and do-it-yourself virtual reality (VR) displays, such as the FOV2GO project [12] and, later, Google Cardboard [37], Samsung's GearVR [93], and similar devices have opened the door to move applications of VR out of the research lab and into the hands of a wide range of users, from computer gamers to scientists, students, and patients suffering from chronic pain (e.g., [95]).

Many data visualizations benefit from the sense of presence that is possible with immersive visualization in virtual reality (VR). In VR, users can analyze spatial relationships in data relative to their own bodies. With a larger field of

view combined with head tracking, VR provides the immersive surrounding context and a kinesthetic depth perception that aid spatial judgements and navigation [111, 112]. The embodied interactions, egocentric perspectives, and natural user interface provided by VR also enable users to bring their trained skills from the real-world to experience their data-driven environments. For instance, immersed inside an heart artery, people think themselves being inside a pipe and find significant structures that may be resulted from blood clots [32]. For drug design, users are zoomed in to a molecular level and configure compositions of modules and perform a docking task by grabbing and dropping them [38]. Also by integrating additional input modalities, historians experience what was like giving a speech on a podium at a historical site that no longer exists [59]. Even though there are various success stories of VR for analyzing 3D scientific data, VR is still on-going research topic. There are still challenges to be addressed to deal with increasing complexity and amount of scientific data [111, 112, 47, 9]. Researchers are revisiting the topic of using and evaluating VR also for analyzing non-spatial data [21, 15, 72, 22, 121], which can allow us to better deal with multi-dimensional nature of scientific data today.

Steven Bryson describes the importance of real-time exploration for scientific visualization and makes the case that VR is a great tool for the exploration [14], and Van Adam et al. elaborate on benefits of VR as a tool for understanding 3D datasets with irregular complex structures [111]. Described in these two papers, however, there are challenges in applying general 3D interaction techniques for 3D data analysis tasks. In the recent survey, Besançon et al. specify such challenges and introduce existing solutions in the field [9]. For example, selecting a distant object with a ray casting technique and extended versions, e.g., [30, 99, 125], would not work with continuous datasets such as 3D scalar fields with no pre-defined structures. Therefore, additional mechanisms such as [115, 97] are integrated to find structures along the ray to make a selection. In visualization datasets, selection techniques often need to work with structures much thinner and denser than those that often show in generic 3D datasets. Jackson et al. integrate haptic feedback and visual filters that remove surround details to ease the selection

process of inspecting neural fibers [50]. Constraint-based interactions can produce more precise and quicker results in shaping geometries that place seed points for streamlines [16] and in navigating geologic reservoir data that have multi-layers of objects with different physical properties [103, 104]. Lastly, in order to navigate in astronomical data where the scale spans in large magnitudes, Fu et al. introduces a multi-touch interaction widget called 'power-of-ten-ladder' that enable users to quickly and continuously navigate through various scales [33].

In this dissertation, our focus is to compare egocentric visualizations of data-driven environments. Portal and 3D Magic Lens techniques [113, 13, 100, 67] could well be used to provide additional data views in the immersed space. However these techniques treat the data view like a small window that only provides a limited view. This can be problematic in cases where the makes of surrounding context is important to data analysis, such as in cases of understanding spatial relations of different digging sites [1, 112]. We extend the portal techniques to provide much more a wider, egocentric, and volumetric views to comparing environments giving the feeling of being immersed in a space composed of multiple environments.

Data analytic tools often provide multiple views of data visualizations with the ability to arrange and combine them [29, 15]. For data comparison tasks, these views are arranged in a spatial layout to enforce a frame of references and consistent arrangements. Coffey et al. compare visualizations of different neck motions on a horizontal plane [18]. Bento Box places multiple views of volume data in a grid layout where instances are placed on a horizontal axis and their detail views are placed on a vertical axis to compare multiple instances at different scales and locations [54]. However, these techniques would not work if the scale of comparing visualizations is much larger than the user, e.g., finding similarities in different virtual constructions of a historical site. A simple solution might be scaling the layouts, but this will result in occlusions. Bento Box technique contains visualizations in cells, but each cell only provides a small window to the comparing visualizations that will clip a large portion of the worlds hiding details that providing surrounding context such as neighboring data elements and

backgrounds. In this dissertation, we introduce a spherical layout with volumetric views that surrounds the user and corresponding interaction techniques to arrange and modify views in the layout for detailed comparative analysis tasks.

## 2.2 Creating and Extending Scientific Visualizations for Public-facing Use-cases

Scientific visualization software such as ParaView and MATLAB offer considerable flexibility in customizing visualizations, which is crucial for expert exploration and analysis but this necessitates the expertise of trained users [40, 43]. Since the primary goal of public-facing visualizations is not necessarily for fostering new scientific discoveries but is for education and communication, the emphasis is often on the accessibility of visualizations. This difference in goals and emphases suggests separate tools for general audiences. In this dissertation, collaborating with the US National Forest Service, we introduce a mobile-based exploratory visualization for general audiences to immerse in data-driven forests at home and learn about changes of forests in the US over a decade using familiar techniques for navigating and viewing geospatial data.

Creating successful public-facing tools/presentations can go through a long process of multi-disciplinary collaborations as demonstrated in [81]. Instead of creating separate tools, Ynnerman, Löwgren, and Tibell take another approach that utilizes existing expert data visualizations in public-facing use-cases by integrating visual components to explain and communicate about what's shown in the expert visualizations [123]. They name these expanded visualizations as "exploration" visualizations, supporting both "exploratory" and "explanatory" use-cases, that enable scientists to easily share their latest scientific results and novice users to explore data if they are interested in. To provide initial guides in exploration, information about hot-spots in an underlying exploratory visualization are provided to suggest starting points of exploration and analysis [122]. Also to provide alternative interaction techniques for novice users, manipulating



visualization parameters could be done by selecting an image from a set of automatically created data views, showing various salient features in the current exploration space [56]. Visuals to provide explanations and guides could be added after visualizations are deployed for a service, for example, by enabling users to leave comments and drawings directly on visualization canvases [80, 42].

In this dissertation, we introduce another example of "exploration" visualizations where scientists create data-stories from underlying exploratory visualizations to explain scientific findings and results. We also address a problem of "exploration" visualizations: by using expert visualizations for public-facing purposes, we enforces general audiences to have hardware setups of expert systems that often are high-end. Our approach is porting visualization results and explanations into the formats so general audiences can view and interact (at a limited fashion) on their low-cost personal devices.

### **2.3 Disseminating Scientific Visualizations for Communication and Collaboration**

When communicating with colleagues, it is often necessary to prepare a separate presentation to guide them through visualizations, and there are multiple ways for creating the presentation. For example, senders provide guides and explanations by sharing individual data views with textual comments [80] or by leaving annotations in visualization canvas [42]. However, we often need more than a single data view in order to break down a complex message into a series of steps and describe scientific reasoning behind interpretations [75, 76]. A form of data presentations that have this characteristic is a data story, and researchers in the field adapted storytelling for communicating about data [62], introducing various authoring tools [5] and usages of other mediums [7]. In this dissertation, we extend the storytelling techniques to make it suitable to use in collaborative data visualizations, for example, by enabling users to interact with stories or to collectively edit these as a way to come to a group consensus on analyzing data.

With the space/time matrix [46], we can categorize collaborative scenarios by

when (synchronous vs. asynchronous) and where these occur (collocated vs. remote). There are other considerations for designing collaborative visualizations. For instance, if we were to encompass a broad range of users, we need to consider their backgrounds and adjust visualization and interaction techniques according to their familiarity with the subject matter and of using the techniques [43]. We also need to support different tasks depending on levels of engagement users have with a visualization as they want to, for example, simply view visualization results, actively explore data, or share results [46]. Also for remote collaborative scenarios, we should be able to support these tasks in various types of devices to broaden the scope of possible use-cases [84]. This dissertation focuses on facilitating asynchronous remote communication with a broad range of users and in settings by enabling users to partake in science collaboration using various device-specific visualization clients.

To serve a broader range of users, scientific visualizations should be accessible outside of a lab environment. Interactive museum installations enable visitors to learn about the state-of-art scientific research using the latest interactive technologies only available in research labs [81, 20]. Or working with curators, the visitors are not only provided with guided tours but also are given the opportunities to suggest off-track exploration [122]. However, these installations are only accessible in the museums. Heer, Viégas, and Wattenberg take public-facing visualizations to the next level by introducing web-based visualizations where general audiences can explore and discuss about data uploaded by other online users [114, 42]. Even though this approach supports almost any device (with a browser), this only works if the visualization techniques can be implemented within a browser environment, which is not the case for many spatial data visualization systems such as ParaView. An alternative approach is to create a data presentation and export this as a video file [48, 5], which makes it widely accessible but does not support interactivity. Intelligent image-based viewers of supercomputer simulations/visualizations [107, 4] preserve some ability to explore data visualizations outside of a native high-end 3D graphics context but do not yet include specific support for collaborative data annotation etc.

In this dissertation, we combine these different approaches of working/presenting data. By porting data explanations as a video file, scientists can communicate essentially with anyone. For recipients who are interested in learning more about the presented data, the video works as a token for reconstructing visualizations in the same analysis software was used to export the video. And for recipients who don't have access to high-end hardware, a mobile client is provided to interactively view the data video and provide feedback to the video creator.

## Chapter 3

# Everyday People

### Worlds-in-Wedges: Combining Worlds-in-Miniatures and Portals to Support Comparative Immersive Visualization

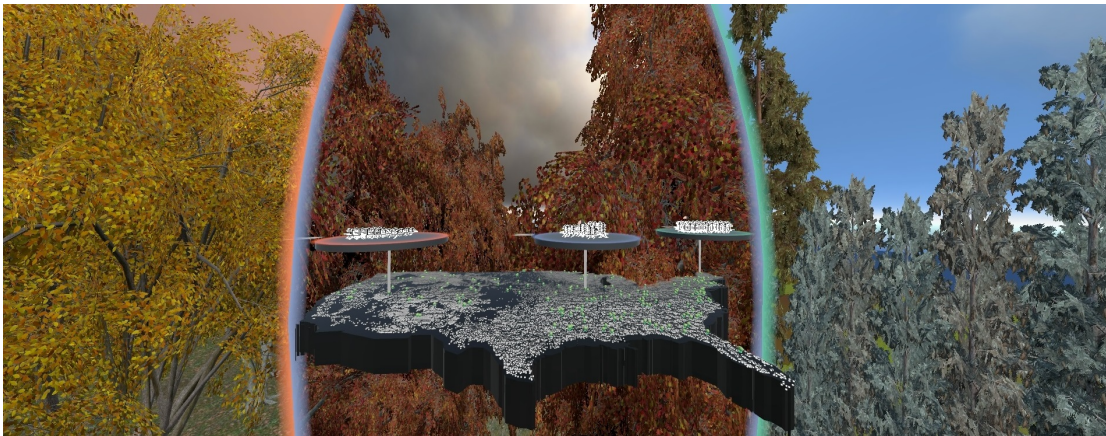


Figure 3.1: The worlds-in-wedges technique is applied here to visualizing three forests from the Forest Inventory and Analysis dataset.

### 3.1 Introduction

In the first research direction, we focus on visualization techniques that provides engaging approaches to explore scientific data. As an example of Everyday Scientific Visualization, the technique enables scientists to present their data in a way that facilitates immersive exploration and visual comparisons using VR technologies. In the conclusion at the end, we consider limitations of this approach as an example of Everyday Scientific Visualization.

Many data visualizations benefit from the sense of presence that is possible with immersive visualization in virtual reality (VR). In VR, users can analyze spatial relationships in data relative to their own bodies. They can also “experience” their data rather than just view it. For example, immersive visualizations make it possible for planetary geologists to stand near a martian crater and analyze slopes, areas in shadow, or other land features using the same spatial reasoning skills they would at a field site on Earth [31]. In VR, archaeologists can use spatial reasoning while analyzing artifacts to naturally refer back to memories of working on the actual dig site (e.g., remember we found a similar lamp to this one *in the trench over there* [while pointing]) [1]. Using a multi-modal, immersive speech-giving interface, scholars of ancient rhetoric can literally *feel* what it was like to give a speech at the hillside of the Pnyx in ancient Athens, recreated under different data-driven conditions for the assembly size and time period [58]. In all of these examples, the sense of presence enabled by VR adds value to the data visualizations, but for VR to be a truly valuable data visualization tool it must do more than immerse users within their data.

One critical task for many visualizations to support is visual comparison [36, 60]. Almost every data-driven scientific study or scholarly work involves some form of comparison, but, as Kim et al. report in their recent survey [60], comparison is an understudied problem in 3D visualization, especially for VR-based visualization.

In VR, whether used for data visualization or some other application, the tradition is to immerse oneself in a single world at a time, but this approach is known

to be problematic for making visual comparisons. As Munzner puts it, “eyes beat memory” [85]. Juxtaposition (side-by-side), superimposition (semitransparent or other forms of overlays), and explicit encoding (when differences are possible to compute explicitly) are three useful, fundamental approaches to visual comparison that, in theory, are all preferable to trying to remember the details of a first dataset while looking at the second, or third, or fifth!

Our specific research is motivated by a collaboration with forest scientists who study data collected by hand by surveyors who inventory each tree within sample plots spread throughout the United States [88]. More than 20 variables are collected to describe the species, size, health, and other parameters of each tree. This data is used, in part, to develop carbon estimates of the nation’s forests, which impact climate policy. Using this data, we have developed algorithms to generate data-driven virtual reconstructions of plots throughout the U.S. Like the planetary geologists on Mars, this enables forest scientists to see and experience their data in a life-size scale that is intuitive, drawing upon their own lived experiences visiting the forests. However, the most interesting thing to do with this data is to compare the plots. How do we do this in VR? It does not make sense to superimpose the plots because they do not share the same spatial reference frame. If not superimposition, then perhaps juxtaposition (side-by-side), but how would this desktop-based technique translate to immersive visualization in VR?

To contribute to understanding these research questions, we introduce a novel interaction and visualization technique called Worlds-in-Wedges. Our approach divides the virtual space surrounding the viewer into pie-slice shaped volumetric wedges and fills each wedge with a different virtual world. By stacking the wedges around a common axis and placing the tracked user at the center, it is possible to create an immersive juxtaposition of spatial data, where the user may look around, using head-tracked stereoscopic graphics to compare multiple worlds. For example, Fig. 3.1, shows a comparison of forests in the West, Midwest, and East of the US.

This core idea can be enhanced with several extensions. It is important to have a strong spatial awareness of one’s location in each of the worlds. So, we utilize a

multi-instance version of the classic World-in-Miniature (WIM) technique [90, 101] to provide a 3D map of each world. We also extend each WIM to function as a multivariate visualization. To convey how the worlds relate to one another (i.e., each plot’s location within the U.S.), we provide a worlds-in-context view. Finally, we consider how to support standard VR tasks, such as navigation and selection in this new style of multi-world immersion.

The specific contributions of this research are:

- A novel VR visualization and 3D user interaction technique for making simultaneous visual comparisons of multiple virtual worlds at real-life scale.
- A volumetric portal metaphor that combines portal and magic lens techniques to support simultaneous immersion in multiple virtual worlds.
- An extension of the traditional World-in-Miniature technique to demonstrate how multi-instance WIMs constructed with multivariate glyphs can be used for immersive visualization.
- Design, results, user feedback, and discussion for a case study based on our motivating application to visualizing the unique US Forest Inventory and Analysis dataset [88].

## 3.2 Related Work

Our research builds upon related work in both data visualization and virtual reality.

### 3.2.1 Experiential Analysis Using VR

Architectural walk-throughs and other first person experiences have long been considered the killer apps for VR. Applications in this style construct data-driven worlds at life-size scale and make it possible for the user to experience the world as in real life. We can walk through historical sites that no longer exists [1, 2, 58] or even places like Mars, where it is impossible or difficult to be [31, 89]. This is

a style of data analysis that is often overlooked since it is less quantitative than other forms. In experiential data analysis, the *feeling* of what it is like to speak to a crowd of 10,000 ancient Athenian citizens is just as important as the ability to accurately measure the dimensions of an architectural reconstruction [58]. This style of first-person, experiential data analysis is what we aim to support, but, unlike these prior works, Worlds-in-Wedges brings this style of analysis to the problem of simultaneous visual comparisons.

### 3.2.2 Comparative Visualization Using VR

Comparison is a crucial task for data analysis [36, 35, 60], but it is not well understood how to facilitate comparative analysis for datasets that are best displayed in VR [60]. A survey published in 2017 found that only 2 out of 41 visualizations for comparing spatial 3D and 4D data utilize VR and points to the need to investigate more in the area. The survey identifies four fundamental approaches for comparative visualization: Superimposition, Juxtaposition, Interchangeable (over time), and Explicit Encoding. One of the two VR comparative visualization examples, a system called Bema [58], supports comparison of multiple historical phases of archaeological reconstruction via an Interchangeable approach. The user is immersed in one world at a time and uses an interactive timeline to switch between worlds via a fade-in-fade-out transition. This worked, in part, because the three historical phases were spatially co-located. In contrast, Worlds-in-Wedges uses what would be called a Juxtaposition approach. The theoretical advantage with this approach is that the data is simultaneously visible, so users rely upon their eyes, not just their memory, to make comparisons. Also, juxtaposition does not require datasets to be able to be spatially registered so that they can be drawn on top of each other in a useful way. Like our work, the other VR example of comparative visualization, a perceptual study by Coffey et al. [17], uses a Juxtaposition approach, but the data is quite different. They compare animated abstract visual representations of neck motions (i.e., biomechanics data), which are small in scale. Our technique is tailored toward comparing life-size virtual worlds, where the impression is that the viewer is immersed in the data rather



than seeing data as a floating object. This style of difference (i.e., *looking-in* vs. *looking-out* tasks) is potentially a critical perceptual distinction for visualization in VR environments [24]. Taking this, along with our desire to include first person VR immersive *experience* as part of the goal of the visualization, we are motivated to explore how comparative visualization in VR might work in the context of the need to “look out” at multiple life-size data-driven worlds.

### 3.2.3 Portals and 3D Magic Lens Metaphors

As in the portal metaphor in VR [13, 100, 67], in Worlds-in-Wedges, another virtual world is only visible through a three-dimensional “window”. However, rather than treating a portal as a window made of virtual glass, our interface does not clip the objects that are between the user and the window frame. This volumetric approach to portals is similar to the volumetric lenses introduced by Viega et. al. [113] and the 3D-Box technique introduced by Kunert et al. [67]. However, these prior examples work with small-scale volumes, such as hand-held tools for applying filters to data within a small volume or as references for travel by teleporting. Our volumetric space is much larger. Also, our wedges are not finite volumes. Aside from the far clipping plane in the graphics renderer, there is no back face to the volume, allowing the user to look out to the world’s horizon.

### 3.2.4 World-in-Miniature Techniques

Traditional WIM interfaces provide a miniature version of a virtual world that acts as a 3D map as well as an interaction space [90, 101]. Many extensions to the technique have been introduced to support features, such as scaling and scrolling [118], automatically selecting optimal views [109], and new ways of interacting with the WIM [101, 68, 116, 19]. Early work demonstrated how multi-instance WIMs can be constructed in order to depict multiple virtual worlds or multiple locations (e.g., different rooms) within the same world [90], a concept that is quite similar to our use of WIMs. The difference in our approach is linking each WIM instance with a corresponding immersive view (in a wedge). Our approach

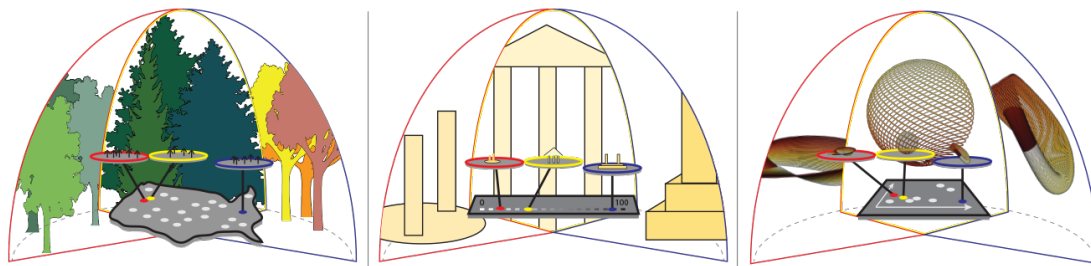


Figure 3.2: The technique is composed of three linked layers, which can be interpreted differently depending upon the dataset. At the worlds-in-wedges level, each wedge always presents an immersive view of one world. At the worlds-in-miniatures level (the discs floating in the middle of the space), miniature versions of each world are displayed using data-driven glyphs or other representations that are helpful in a bird’s eye view. Finally, at the worlds-in-context level, the relationships between the different worlds that can be activated in the display are visualized. On the left, in our forestry example, the context is spatial – each world corresponds to a plot at a specific latitude and longitude where the forest service has collected data, and worlds for three such plots are currently active. In the middle, we imagine an application to a different dataset where the relationship between multiple worlds is temporal rather than spatial. Here, multiple worlds are contextualized on a timeline, as in multiple historical reconstructions of an archaeological site. On the right, we imagine a more abstract relationship. Here, some high dimensional datasets (e.g., mathematical functions, parameterized simulations) are related through a 2D plot that displays a dimensionally reduced version of the data.

also incorporates another visual layer, placed on the bottom of WIMs, to convey how these WIMs are related to another. Finally, rather than rendering an exact miniature version of each world, we render an abstract data visualization of the world, where the terrain is intentionally simplified and realistic trees are replaced with multivariate data glyphs.

### 3.3 The Worlds-in-Wedges Technique

This section describes the visualization and interaction techniques that make up the new approach to immersive comparative visualization we call the Worlds-in-Wedges technique. The technique requires a head-tracked stereoscopic VR display and a 6 degree-of-freedom tracked wand that is held in the dominant hand. As is common in today’s commercially available VR hardware, the wand must have a primary button (e.g., a trigger button) as well as a touchpad or joystick to serve as a secondary button and provide 2D analogue input. Input from the non-dominant hand is limited to a button, which can be provided by another VR controller or a low-cost device, such as a wireless mouse. Our current implementation uses the HTC Vive VR display and its two controllers.

#### 3.3.1 Visual Layout: A Linked, Three-Level Visualization

The Worlds-in-Wedges technique is composed of three-levels of visuals, as diagrammed in Figure 3.2.

##### Level 1: Worlds-in-Context

The worlds-in-context layer visualizes the relationship between the different virtual worlds. The specific relationship to display is determined by the comparison task at hand. In this chapter, we fully develop the forestry example, which is based on comparing different physical locations. In this case, it makes sense to contextualize the different locations on a map. However, to assist others who might wish to apply the technique to other non-spatial datasets, we suggest two other possible mappings in Fig. 3.2. For comparing changes of a historical site at different points of time, the Worlds-in-Context layer could be realized as a timeline, where each world would be represented with a marker placed along the timeline. For comparing more abstract data, the Worlds-in-Context layer could be realized using a 2D plot, for example a scatter plot or a plot of a dimensionally reduced version of the data.

### **Level 2: Worlds-in-Miniatures**

The worlds-in-miniatures layer is a multi-instance version of the classic World-in-Miniature VR interface [101, 90]. As in the traditional WIM, each WIM is a 3D map of the corresponding virtual world that can also be used as an interaction space. There is a visual indicator within the miniature world for the user’s current location. However, rather showing an avatar of the user, our WIM shows a rendering of the wedge that is displayed in the next layer. We also reinterpret WIMs as a data visualization tool that complements the immersive display by displaying multivariate data-driven glyphs that reveal more information for each object in the world rather than simply rendering a scaled-down version of the same 3D graphics used to render the immersive scene.

### **Level 3: Worlds-in-Wedges**

The worlds-in-wedges layer, which serves as inspiration for the name of the overall technique, divides the virtual space surrounding the user into wedge-shaped volumes, where each wedge acts as a volumetric portal, displaying a portion of a world. The wedges provide the first-person, head-tracked, stereoscopic views of virtual worlds, and only the portion of each world that falls into the wedge volume is rendered.

The three layers are visually linked using lines and corresponding colors. Each WIM is linked with a line to a point on the worlds-in-context layer. When the position of the WIM changes, the line’s end point moves as well to preserve the visual connection. Each WIM is linked with the corresponding wedge using a categorical color coding; the color of the WIM outer ring and that of the wedge’s frame is the same. When a new virtual world is activated, a new World-in-Miniature and World-in-Wedge pair is created, and the pair is assigned a new hue to mark it as unique. To help the user maintain spatial awareness, the WIMs are also linked to the wedges by orientation – that is, the WIMs are always rotated so that the mid-line of the miniature wedge drawn on each WIM as an indicator of the user’s current position and orientation is aligned with the mid-line of the

larger wedge.

### 3.3.2 Interactive Techniques

Worlds-in-Wedges enables exploratory visualization through interaction techniques. These support manipulating the views as well as standard 3D user interface tasks, such as selection and navigation, which need to be adjusted to the new situation of interacting in wedges.

#### Activating and Deactivating Virtual Worlds

A data analysis session begins with only the worlds-in-context layer visible. To add a new WIM and wedge pair to the visualization, the user selects a point of interest within the worlds-in-context layer using a laser pointer. Depending on the dataset, it may be difficult to select this small target, so we utilize the flashlight technique [73] to select the closest point within a threshold of the ray-plane intersection. When a selection is detected, the ray changes its direction and snaps to the selected point, providing visual feedback to the user. When a wedge is added or removed, the size and location of each wedge is automatically updated to display each virtual world with the largest, non-overlapping view possible within a preset total viewing angle. It is possible for the total angle to be a full 360 degree view, but we often limit the view to 220 degrees for our application, which has a natural preferred orientation (North is forward and the user stands South of the US map looking down on it as if laid on a virtual table). The WIM positions, floating above the worlds-in-context layer, are calculated using a spring system. Each WIM is anchored to its position on the worlds-in-context layer and tries to locate itself directly above this position but is pushed away by other WIMs to avoid overlap.

Deactivating a virtual world is done by selecting and grabbing onto the corresponding WIM using the dominant hand’s laser pointer and trigger button and moving it down toward the worlds-in-context layer. This activates a semi-transparent bounding plane, just above the worlds-in-context layer, and when the WIM is moved below this threshold, the world is deactivated.

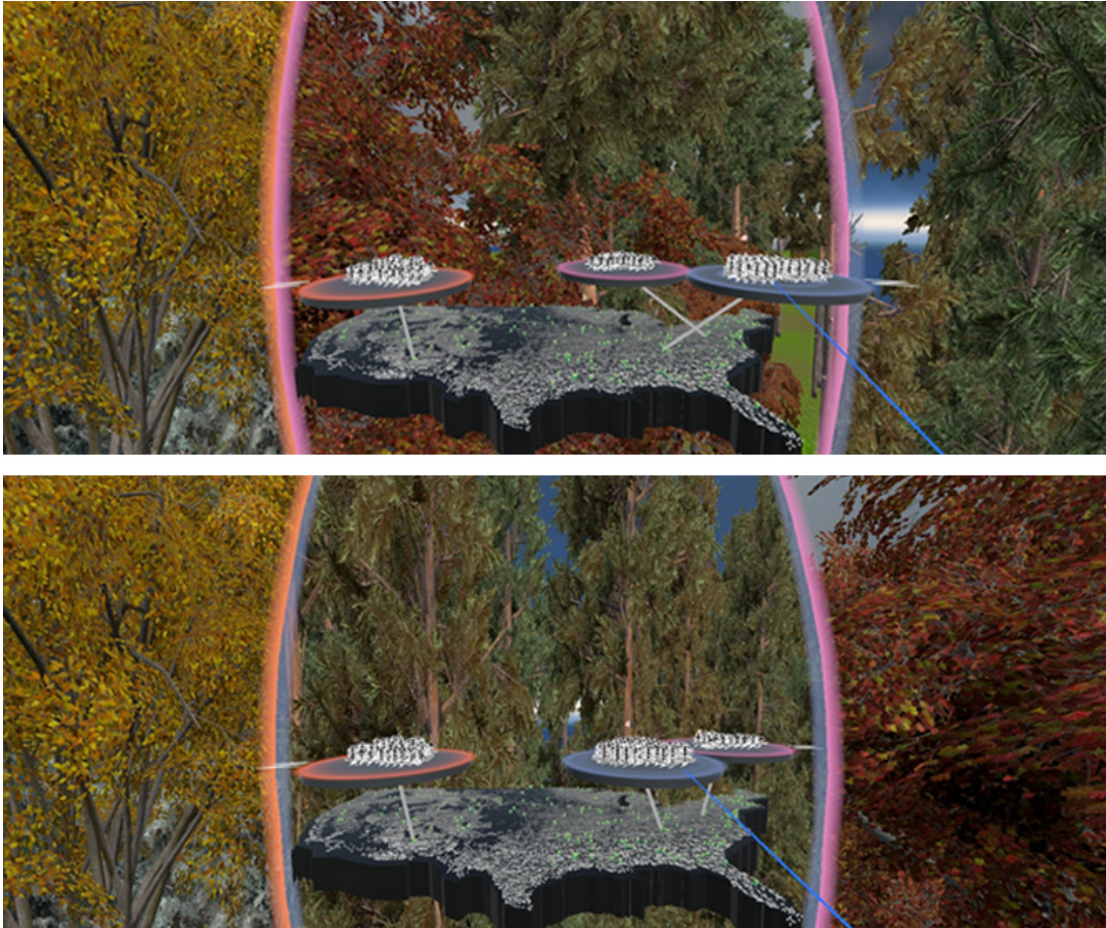


Figure 3.3: The horizontal positions of WIMs affect the order of the wedges. From the top screen capture to the bottom, the user has moved the blue WIM to the center, which moves the corresponding wedge to the center.

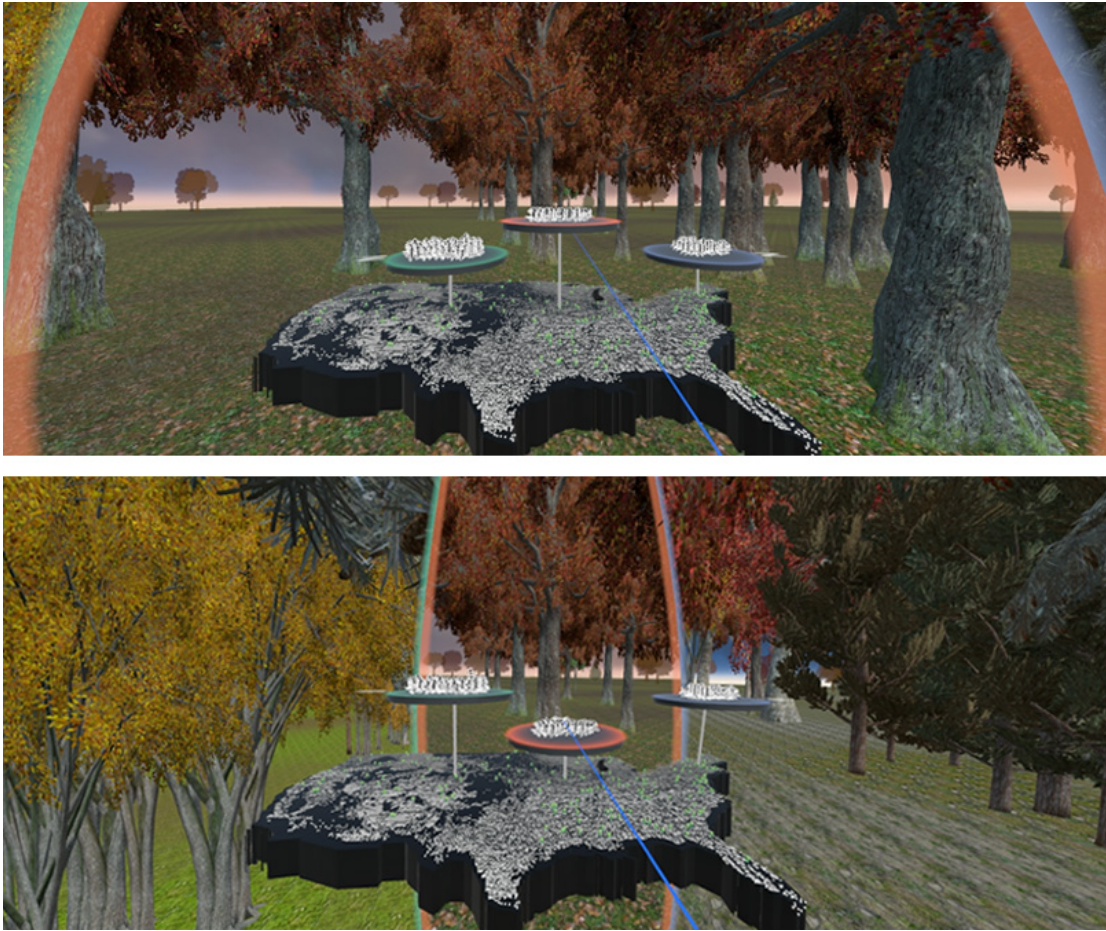


Figure 3.4: The angle of each wedge is tied to the vertical position of the corresponding WIM. In the top image, the user has placed the orange WIM higher than others to see the corresponding world in more detail. In the bottom image, the orange WIM has been lowered, causing the angle of the corresponding middle wedge to shrink in proportion.

### Arranging Visuals in the VR Space

During comparison and discussion with colleagues, it is often useful to rearrange the display. For instance, the user may wish to place a specific world in the center to make it a baseline for comparing other worlds to the left and right. Or the user might wish to place closely related worlds next to each other, forming subgroups. This is accomplished by grabbing onto the WIM of interest and moving it horizontally as illustrated in Fig. 3.3. The relative positions of the WIMs set the ordering of the wedge views. Thus, when a WIM is moved to the left of another WIM, the corresponding wedge will swap places with its neighbor to the left.

It is also useful to resize the wedges based upon the current task. Worlds can be completely deactivated as described above, but this is not always desired because it takes time to find the world again and reactivate it. Instead, if the user wishes to zoom in and focus on one or two of the active worlds temporarily, then this can be done by grabbing onto and moving the corresponding WIM vertically. As shown in Fig. 3.4, the relative vertical positions of WIMs are used to set the angle of each wedge, like a vertical slider. The angle for each wedge is computed based on its WIM's position relative to a global maximum and minimum height for all WIMs using the following equation:

$$a_i = \frac{h_i}{\sum_{j=0}^n h_j} a_{total}, \quad (3.1)$$

where  $a_i$  is the angle of  $wedge_i$  that corresponds to  $wim_i$ ,  $h_i$  is the normalized height of  $wim_i$  relative to the global max and min,  $n$  is the number of active virtual worlds, and  $a_{total}$  is the total angle of the wedges.

When interacting with either the WIMs described here or the wedges (via the navigation techniques described later), the interface follows a consistent approach in terms of responding to user input. All active worlds respond to head-tracking input by updating the view and projection matrices used to render the scenes, but only one WIM and wedge pair is considered currently in focus in terms of receiving input from the hand controllers. The wedge in focus is determined based upon a virtual laser pointer that extends out of the dominant hand's controller. Although



this pointer can be thought of as “selecting” the active wedge, it is important to note that the wedges are large; so, this does not have the problems typically associated with laser pointer selections in VR. Instead, the technique is designed to feel to the user as if the wedge they are facing, as they naturally turn their body to look, becomes automatically focused.

The one useful exception to the focus rule is when the button held in the non-dominant hand is depressed. We treat this as a modifier, like the Control key on computer keyboards it modifies the current operation so that it applies to all active worlds rather than just the one in focus. When applied to the wedge resizing operation, this modifier means that the angles for all of the wedges are adjusted when one is moved. When the WIM being moved goes up, the other WIMs go down by the same amount. This is useful when the user wants to quickly focus on just one world. Conversely, when the WIM being moved goes down, the other WIMs go up, nearly hiding the world being moved to give the most display resolution to the other worlds.

### **Accessing Detailed Data on Demand**

Pointing with the laser to select an individual object within the 3D wedge scene selects it and this pops up a panel filled with detailed data about the object (see Fig. 3.5). The panel is placed right next to the dominant stylus and moves along with it. In the case where there are multiple wedges, hence multiple worlds, only the objects in the wedge currently in focus are considered for the ray-intersection.

### **Navigating in Wedge Space(s)**

The 2D analogue input (joystick or touchpad) on the dominant hand’s controller is used to perform navigation. We assume the worlds are large, like terrains, somewhere we typically walk. Therefore, we support walking-style and flying-style navigation.

Walking mode is active when the controller is held in a normal, horizontal orientation. Pressing forward on the touchpad or joystick moves in the forward

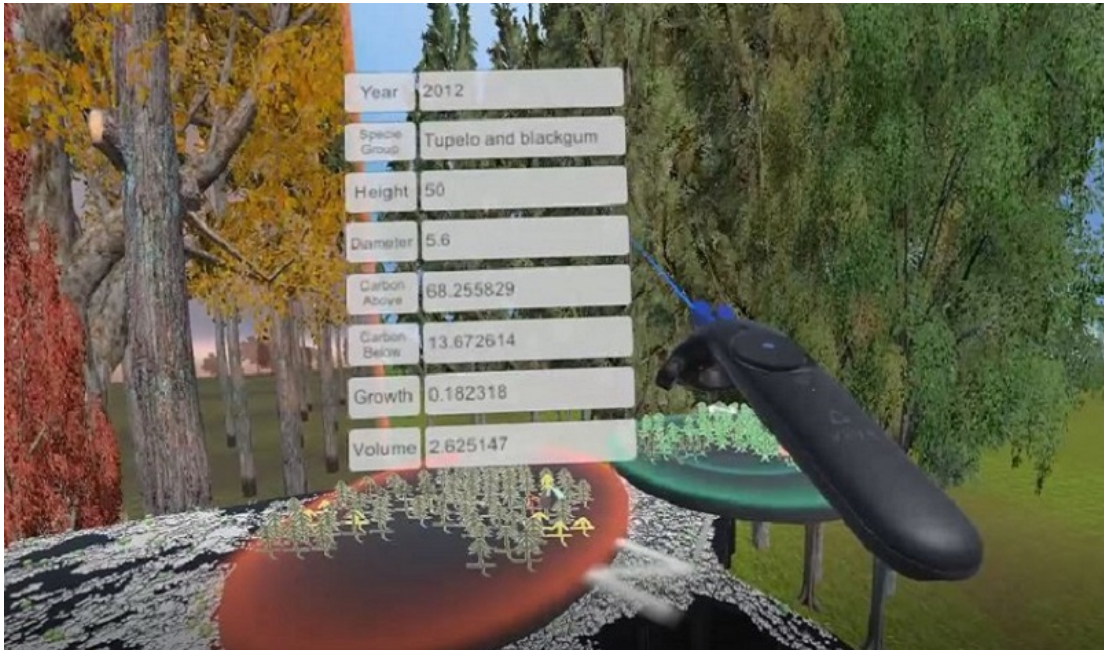


Figure 3.5: Ray-casting selection with a virtual laser pointer is used to identify objects of interest in the 3D scene for closer inspection. After pointing to a tree, a pop-up panel shows detailed data on demand.

direction within the world that is currently in focus. Pressing back moves backward, and so on. Rotation about the vertical axis is initiated by pressing down on the center nib of the touchpad or another secondary button on the device. The angle of rotation is then set based upon the change in rotation of the controller. Clutching is used to make large rotations. When the touchpad of the HTC Vive is used to implement this interface, the circular center nib on the touchpad provides a useful haptic aid to the user, making it clear without looking which part of the pad to use for rotation vs. translation.

Flying mode is activated when the wand is pointed up. In this mode, forward and backward touchpad inputs are mapped to flying up/down movement. To make it easy to maintain input focus on the wedge of interest during this operation, the direction of the laser pointer is adjusted so the ray shoots down from the wand instead of forward (see Fig. 3.6).

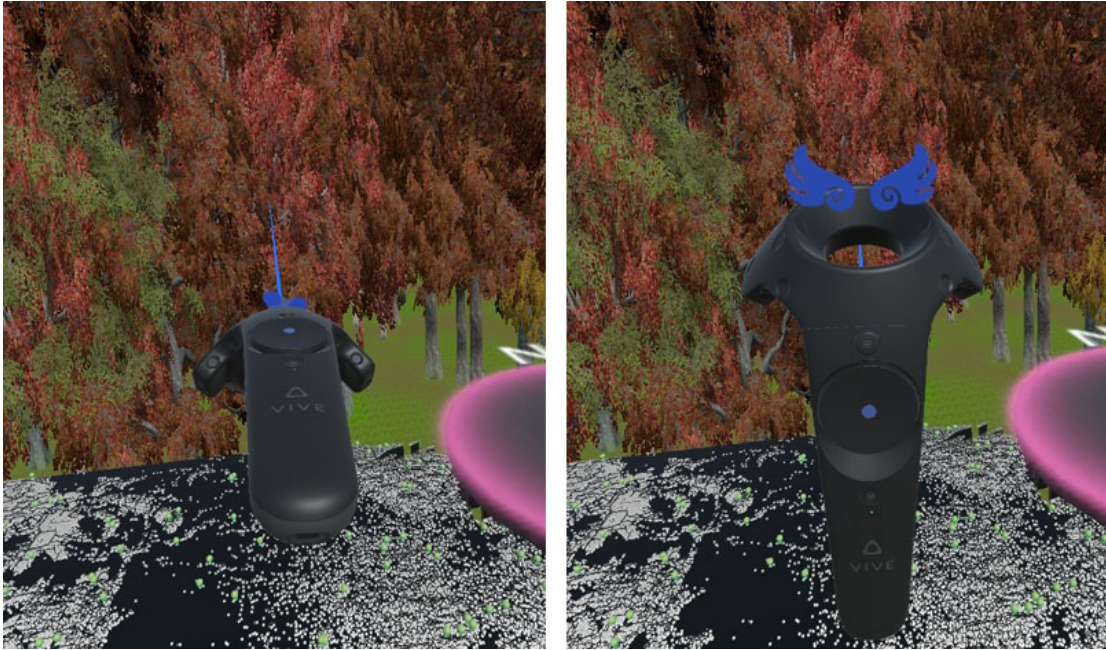


Figure 3.6: Left: walking mode is active when the controller is held in a horizontal orientation, and touch input is mapped to horizontal movements. Right: pointing the wand upward changes to flying mode, where the ray shoots out from the bottom of the wand, and touch inputs are mapped to vertical movements.

When the non-dominant hand’s option button is depressed, placing all active worlds in focus, navigation happens simultaneously in all worlds.

### Rendering Multiple Worlds

Multi-world rendering is implemented using the stencil buffer and a multi-pass technique. To setup the stencil buffer, a sphere is rendered with a custom fragment shader that computes the wedge shapes and outputs a unique ID number to the stencil buffer for each wedge. Then, in a second pass, each world is rendered using a stencil test that passes only for the corresponding wedge. Users can see the curve of the edges of the wedges along the sphere, but, other than these edges, the sphere used to setup the stencil buffer is not directly visible.

It is useful to think of the user as located within this imaginary sphere. Since,

in VR, the virtual camera positions are defined through head tracking, we do not move the virtual cameras directly when users navigate through the worlds. Rather, we translate or rotate the worlds relative to this imaginary sphere that the user occupies.

Other rendering techniques would also be possible, however, the stencil-based approach is sufficient for our application, with frame rates above 30 frames per second reported for all of the examples pictured in this chapter.

### 3.4 Forestry Case Study and User Feedback

The description of the visual layout and interaction techniques in the prior section is intended to be applicable to use with any VR application that can: (1) render head-tracked, stereoscopic views of a data-driven, life-size virtual world, (2) use clipping planes to draw that world in a wedge, and (3) use ray-casting to select specific objects in the scene for displaying details on demand. However, visualization designers will typically want to adjust details of how to represent data within each wedge (e.g., realistic rendering vs. abstract) and within each WIM (e.g., using glyphs or simply a scaled version of the full-size scene) based on the particular application. In this section, we describe our own application-specific design decisions, results, and user feedback, which are useful as a first evaluation of the technique and also, more broadly, as a case study of implementing a complete data VR tool for visualizing an important actively researched dataset in collaboration with domain scientists.

We applied Worlds-in-Wedges to the problem of comparing plots from the US Forest Service’s Forest Inventory and Analysis dataset, which contains more than 20 million trees (20,595,807) across 629,644 forested plots systematically located across the U.S. [88]. Data have been collected via in-the-field measurements on a periodic basis since 1928. Our virtual reconstructions use the tree-level data, which include detailed measurements on diameter, height, species, above and below ground carbon content, damage, growth, and more. The above-ground and below-ground carbon content data are particularly interesting because these factor

into estimates that impact the nation’s climate policy.

The data is collected following a regular sampling. Each plot consists of four circular subplots of radius 24 feet. The first subplot is located at the center of the plot, and the other three surrounding it are separated by 120 degrees each. Detailed measurements are made for every tree within the subplots, and additional data on land use and slopes are also collected.

### 3.4.1 Implementing the Three Layers

The visualizations created using this data are pictured throughout the chapter.

#### Wedges

Each wedge is a life-size data-driven reconstruction of each plot. Each tree within the plot is rendering using a 3D model selected from a set of models (Fig. 3.7) based on the tree species data variable. The model is then non-uniformly scaled based on the height and trunk diameter and positioned within the plot using a combination of three data variables: azimuth, distance, subplot id.

The terrain for each plot is procedurally generated based on the data variables available within each subplot (aspect ratio, slope, subplot id). This calculation is not straightforward because the data were not intended to be used to reconstruct an actual terrain map. Thus, our algorithm reproduces a plausible terrain given the ground slope data, which is only available at the subplot level. For each plot, the data is sufficient for defining just 8 height constraint points, one at the center of each subplot and one at the highest point along the outer radius of the subplot. The center point of the center subplot is the first constraint, we treat this as height 0. Then, using the aspect ratio and slope variables, we compute the height and location for the highest point within the center subplot. This is the second constraint. The algorithm treats this center subplot as special, assuming that its slope, which defines a plane in 3-space, persists to some degree throughout the entire plot. So, the heights for the center points of the three surrounding subplots are determined based on their locations within this plane. This adds three more

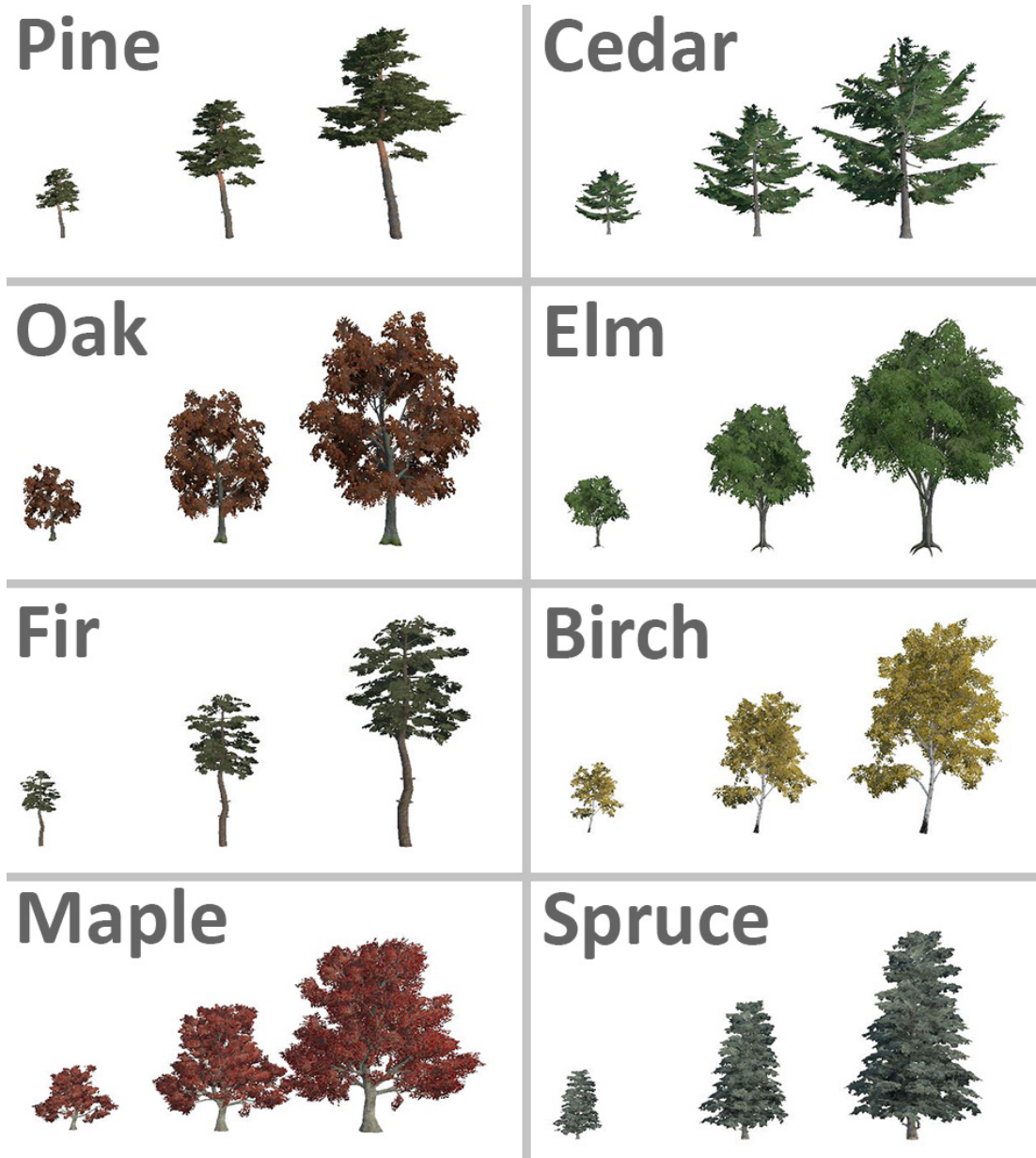


Figure 3.7: Tree models used for eight of the tree species. In the data driven forests, the models are non-uniformly scaled to match the heights and trunk diameters recorded in the forest inventory data.

constrain points. Finally, the highest point within the outer subplots is determined by offsetting from the height at its center using the local slope and aspect ratio. This adds the final 3 constraint points. Using the eight height constraint points as input, the height of each vertex on the terrain grid,  $h(i)$ , is computed using an inverse distance weighted average,

$$h(i) = \sum_{j=1}^8 \frac{1}{d(i, j)^p}, \quad (3.2)$$

where  $d(i, j)$  is the 2D distance from terrain vertex  $i$  to constraint point  $j$  and  $p = 4$  (an empirically determined constant).

Since the plots do not extend forever, we also include some billboard trees in the style of architectural renderings around the outer region of the plot to give the impression that there is uncertainty about the data beyond these bounds but that it's likely the trees do not end as abruptly as shown by the 3D models.

## WIMs

The most straightforward approach to creating WIMs that are appropriate for use in the worlds-in-miniatures level is to render scaled down versions of the 3D scenes. In a typical graphics engine, this can be accomplished by rendering each scene twice, once at normal scale for the wedge, and a second time with a simple scaling transformation matrix applied for the WIM. However, we construct a more sophisticated data visualization to display on each WIM.

Our approach is to construct an abstract glyph-based visualization for each plot (Fig. 3.8). Each tree is drawn as a data driven glyph rendered as a billboard. The glyphs are color coded by tree species group, and, as illustrated in Fig. 3.9, each glyph encodes three important variables: (1) tree height and (2) above ground carbon content, and (3) below ground carbon content. In this way, the WIM visualization adds detail that is not visible in the realistic 3D representation, making it useful not only for wayfinding and spatial context but also as a complementary multivariate data visualization. Within each WIM the billboards are rendered in a non-overlapping way using a mass-spring system to increase legibility.

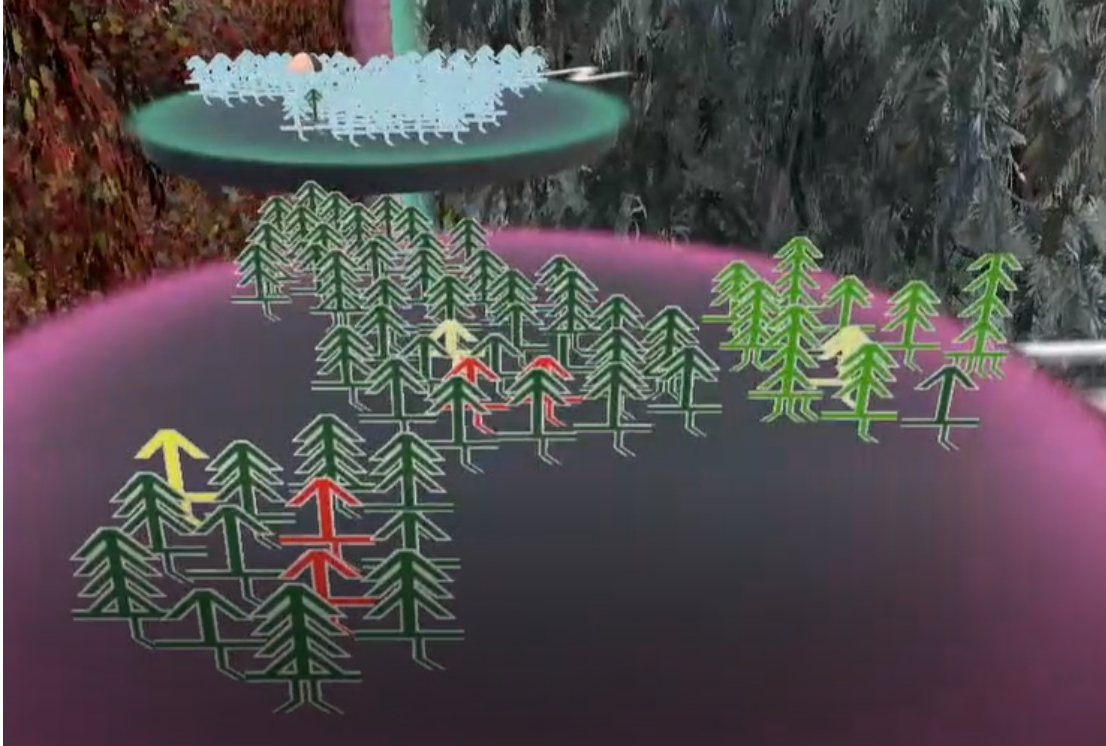


Figure 3.8: Tree glyphs rendered as non-overlapping billboards on a WIM.

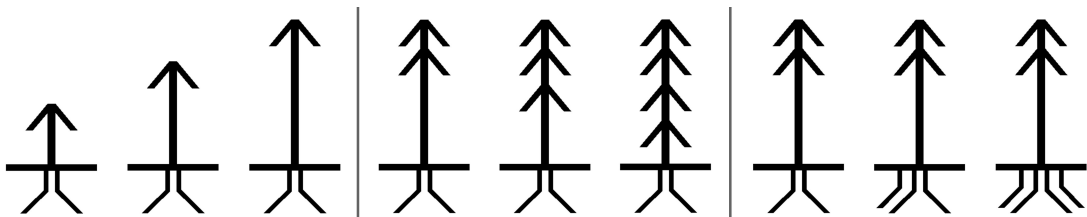


Figure 3.9: Detail of the glyph design. Tree height is mapped to the height of the center line of the glyph. Above ground carbon is mapped to the number of branches on the trunk. Below ground carbon is mapped to the number of underground roots.



## Context

For this application, the worlds-in-context layer is a US map, and the dots on the map represent the plots in the data. Our current implementation loads data-driven worlds for a subset of 200 of the available plots. The locations of all of the plots are displayed with white dots, and the 200 plots that can be activated as virtual worlds are indicated on the map as green spheres.

### 3.4.2 User Feedback from Forest Scientists

Our interdisciplinary team has iteratively co-developed several versions of the software over the course of multiple years. During this time, the visualization researchers have collected and responded to feedback via design review sessions every few months. To provide a first evaluation of the technique, our team treated the most recent collaborative session as a summative design review. The methodology involved two forest scientists working with Worlds-in-Wedges over the course of approximately two hours and using a talk-out-loud protocol while completing an open-ended data exploration task. One forest scientist at a time used the HTC Vive display and controllers while the other watched the interaction on a large TV display setup to mirror the view rendered in the VR headset. The scientists switched roles part way through the session. The visualization researchers began the session with a tour through the features available in the current version of Worlds-in-Wedges and then took detailed notes and prompted discussion to understand points of success and confusion.

The scientists confirmed expected trends and made new discoveries. For example, looking at a forest at a bird-eye view, one scientist pointed out a region where there is a clear boundary. On one side, the trees are much shorter than on the other. This suggests the two areas have different land uses – the side with shorter trees is part of a plantation whereas the other side is not. Specific land usage information is included in the dataset and is something to incorporate into the visualization in the future, but it was interesting to note that, in this instance, users did not need that variable to be explicitly displayed. Given that they were



Figure 3.10: A plot in the state of Maine (Northeastern U.S.) is being observed from a bird-eye view. The tall trees are Eastern whites and red pines, surrounded by much shorter spruces and balsam firs.

able to immerse themselves in the data, they could see the pattern simply through being there. This example led to a discussion of the potential to use the tool for story telling. For example, telling the story to the general public of where tree plantations are located and how they are managed via a methodology that makes it possible for people to actually see what this means.

As the other scientist was flying around in another forest, he found an example of a few trees that are much taller than the others nearby (see Fig. 3.10). At first, he thought this looked odd, perhaps a mistake in the data. Then, pointing the ray at the trees to bring up details on demand, he determined that the tall trees are Eastern white and red pines and the short ones are spruces and balsam firs. Thus, the data and visualization actually makes sense given the species and how these would grow within a forest in the northeastern US. The scientists remarked that this is the type of information that is present in the data tables they currently use for analysis, but that the intuitive meaning is lost in those tables. In contrast, with the immersive visualization, the meaning of the data (e.g., the distribution of the tree species, the degree to which some trees differ from the surrounding forest) is immediately clear.

Another visual comparison involved multiple pine forests across the US. During

this analysis, the scientists first activated three plots, one in the northeast, one southwest, and one southeast. They observed the three forests in equal-sized wedges to see the overall pattern. Then they raised one WIM to see that plot in more detail. Then, they repeated the same for the other forests, moving back and forth between focusing on one forest or another. In general, when comparing data with juxtaposed views, it is often the case that overall patterns are easily seen but there is a need to zoom in to examine details [60]; this frequent wedge-resizing behavior seems to be one way to support this in VR.

Several suggestions for refinements were also captured. The scientists identified during data analysis that flying to the same height above the ground in all worlds would be a useful way to judge tree heights. This is supported in the current interface. The simultaneous navigation mode supports coordinated movement, but it is coordinated relative movement, not absolute, so if you do not start on the ground in each world, then the heights will not match as you move all views together. Thus, it would also be useful to include a lock feature in order to move the user to the same height across all of the wedges. There was also a suggestion to adopt different gestures for rotating the worlds via WIMs. Since the WIMs look like turn-tables, there is a natural affordance to grab and rotate them via a direct manipulation. It may be that a gesture like a tabletop interface [39] would be a good complement to the current interaction. One scientist reported that the WIMs and the Worlds-in-Context views sometimes got in the way of focusing on the immersive views, suggesting a feature dismiss them on demand or automatically fade them out when the controllers are not being moved.

## **3.5 Discussion and Future Work**

The research raises several interesting implications and future directions.

### **3.5.1 New Basic Research in Multi-World Presence**

Our current forestry application applies different background-level details (sky maps, ground textures) to the non-data-driven elements in each forest to reinforce

the sense that each plot is different. We have done some early experiments with extending this idea to a multi-sensory experience, using sound as an additional cue for distinguishing between the different worlds. In this mode, each wedge is assigned its own “soundscape” (e.g., birds, crickets, wind, water), and the gain applied to each sound is set in proportion to the angle of the corresponding wedge, so as the user adjusts the relative sizes of the wedges, zooming in to focus on one world of interest, the sounds of that world become more prominent. The aim is for the user to feel “more present” in the larger wedge(s).

Although this soundscape feature was added late to the visualization, almost as an after thought, it has sparked some of the most exciting ideas for future research. The topics of embodiment, presence, and useful perceptual illusion (e.g. [6, 105, 91]) show up again and again in the literature and session themes at the major conferences. However, we are not aware of any other VR research that studies these aspects in a “multi-world presence” setting. We believe this concept could open up a new line of basic research in presence, embodiment, and perceptual illusion, and that the potential to use field-of-view, audio, and other cues to adjust levels of presence in multiple simultaneously visible virtual worlds deserves study at a more basic research level. It would be interesting to learn what factors best promote multi-world presence. On the other hand, there is also a possibility that immersion in multiple worlds could break users’ sense of presence within any one world. Thus, although we believe there is exciting potential, more studies are required to understand this effect.

### **3.5.2 Additional Data and Representations**

A useful but more straightforward extension of the current forest visualizations is to include additional variables in the data-driven virtual forests. For example, the forest inventory includes realistic contextual information on adjacent water bodies, marshlands, and land use. Incorporating these along with additional procedurally generated elements should increase “perceptual realism” [25], adding to the goal of experiential analysis discussed earlier. In addition, recent work on statistical forest modeling [117] should make it possible to extend the forest reconstructions

beyond the limits of the sampled subplots to create continuous virtual forests. Perceptually, it would be easier to read the height of trees on a bar chart as compared to being in the forest, but we have intentionally made a trade-off in that regard, privileging immersion and experience over data legibility. In the future, we envision transitioning between multiple visual representations, some realistic and some abstract.

We are interested in applying the Worlds-in-Wedges technique to other dataset. The diagrams in Fig 3.2 already demonstrate how small adjustments to the worlds-in-context layer could make the technique applicable to worlds that are linked by time (e.g., comparing structural changes of a historical site at different points in time) or datasets linked in some more abstract way (e.g., parameterized simulation ensembles). We are also interested in exploring the potential of wedges that can be repositioned to focus on looking up (e.g., comparing multiple construction phases of the Sistine Chapel ceiling).

### 3.5.3 Insight-Based and Low-Level Evaluations

This research has been motivated directly by an interdisciplinary collaboration. So, it naturally includes a significant data processing and system building component as well as an initial evaluation via expert user feedback for interdisciplinary collaborators. However, the technique would benefit from additional evaluations in other contexts. On one end of the spectrum, a formal insight-based evaluation with domain experts [94] would be useful. On the other end of the spectrum, it would also be useful to test a synthetic abstract dataset with non-expert participants. In both cases, we are confident based on the current case study and evaluation that data comparison tasks performed in life-size VR data-driven worlds would be faster and more accurate when performed using Worlds-in-Wedges as compared to the status quo approach, immersion in a single life-size virtual world at a time. However, it would be interesting to characterize the degree of the benefit both for scientific analyses and for other uses, such as storytelling.

### 3.6 Conclusion

Worlds-in-Wedges is a new VR-based visualization and user interaction technique for making simultaneous visual comparisons of multiple virtual worlds at a life-size scale. The approach extends Portal and WIM techniques to create a unifying metaphor for comparative immersive visualization. Within the application to comparing plots from the US Forest Service’s Forest Inventory and Analysis dataset, the technique was successfully used to confirm known and discover new trends in the data. Scientists also suggest the technique shows promise as a public-facing storytelling tool. This application serves as a case study both for evaluating the current technique and, more generally, for how VR can be applied to problems in scientific visualization via interdisciplinary collaborations. Our discussion of lessons learned raises several important directions for future VR research, including study of multisensory cues for evoking different levels of presence in environments that simultaneously display multiple life-size virtual worlds.

As an example of Everyday Scientific Visualization, the presented approach makes high-end scientific data accessible for general audience by visually representing the data in a fashion already familiar to people and by employing engaging navigation techniques similar to those in games. Additionally the technique supports simultaneous viewing of multiple data-driven worlds that provides a basis for comparison-based data exploration and communication. Thus, this work makes this high-end scientific data accessible for everyday people who are curious about the science behind it and interested in coming up with their own insights.

However, when we consider accessibility to technologies, this approach has a limitation of requiring special hardware set-ups and high-end workstations, which makes it difficult for the public to use the visualizations at home or schools. In the next chapter, we describe alternative visualization approaches that provide more accessible options for exploring the FIA dataset.

## Chapter 4

# Everyday Devices

### Linked View Visualization Using Clipboard-Style Mobile VR: Application to Communicating Forestry Data



Figure 4.1: Constructing a low-cost, mobile VR device as shown makes it possible to hold the display up to ones eyes and see a stereoscopic 3D visualization and also interact with a linked complementary 2D visualization displayed on the bottom of the screen.

## 4.1 Introduction

This chapter focuses on the research component *Everyday Devices* and introduces an application that enable common visualization practices on low-cost devices. This lightweight mobile app has limited exploration capabilities but provide users more accessible visualizations for education and training.

Recent advances in low-cost and do-it-yourself virtual reality (VR) displays, such as the FOV2GO project [12] and, later, Google Cardboard [37], Samsung’s GearVR [93], and similar devices have opened the door to move applications of VR out of the research lab and into the hands of a wide range of users, from computer gamers to scientists, students, and patients suffering from chronic pain (e.g., [95]).

We are interested in exploring the potential of these new widely accessible forms of VR for data visualization. Inspired by the iNVerse low-cost viewer developed at USC’s MxR lab [12], we fitted an iPad with a pair of low-cost lenses that fit over the top third of the screen (Figure 1). This makes it possible to turn the top third of the device into a stereoscopic display. Our software interfaces with the rotational sensors on the iPad to update the display based upon the user’s current heading, thereby creating an effective low-cost VR device that users simply hold up to their eyes. What is unusual about this form factor when compared to others, like Google Cardboard, is that the bottom two-thirds of the device can also be used for data visualization and for multi-touch input. Thus, the device is like a clipboard that provides a 3D view when held up to the eyes and a complementary 2D view when held in the hands.

We believe this holds promise for data visualization because of the potential to present complementary data in the two views. Visualizing data in “multiple complementary linked views” [87] is a foundational technique in 2D data visualization. The idea is less common in 3D immersive visualization of spatial data, but there are some examples (e.g., [86]), including several that link a 2D multi-touch table with a VR 3D data view [16, 59]. However, these prior systems have required large, custom hardware.



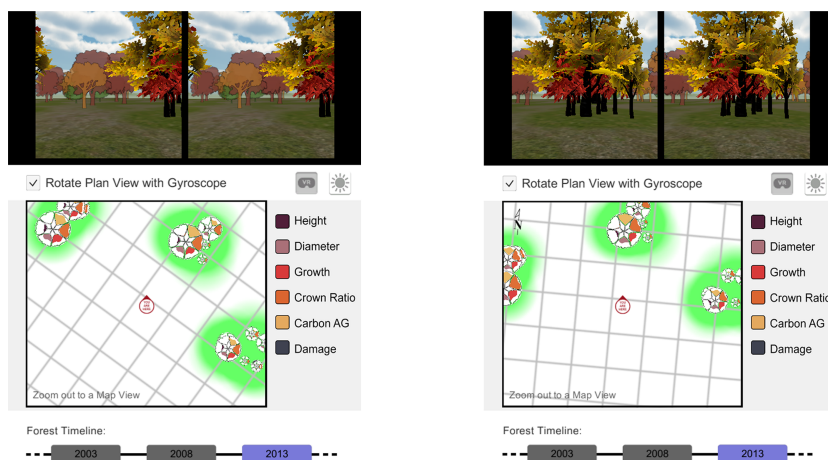


Figure 4.2: The visualization before (left) and after (right) a multi-touch rotation gesture was applied in the 2D view.

This chapter contributes the first example of a 2D plus 3D VR linked view visualization on a mobile device, which makes it practical to use in many settings, including K-12 classrooms.

## 4.2 Application

To demonstrate the potential with a real-world dataset, we have used the platform with interdisciplinary collaborators to visualize the US Forest Service’s Forest Inventory and Analysis dataset, which contains more than 20 million trees (20,595,807) across 629,644 forested plots located across the U.S. [88]. The prototype visualization includes just three of the plots, selected by forest scientists as interesting, representative samples of a forest with high basal area, a forest with significant recent growth, and a forest with significant changes in tree count over the years. Each plot is sampled via in-the-field measurements every five years, and our visualization includes measurements for 2003, 2008, and 2013. For each plot, measurements are made for every tree that falls within the bounds of 4 circular subplots; hence, the pattern of trees clustered within 4 circles seen in some of our imagery.

Although the tool could certainly be used for exploratory data analysis, the primary objective of the scientists in this case was to explore the potential of more engaging modes of presenting their data to the public. They are particularly interested in outreach to children; thus, we decided to employ representational 3D models of the different tree species for the 3D view of the forest with the plan that the scientists and teachers could use the tablet devices that are now common in K-12 classrooms to lead students in virtual field trips to the forests to discuss change over time.

### **4.3 3D View and Interaction**

The 3D view consists of a data-driven, dynamically generated 3D forest scene, where the 3D tree models are selected and scaled based upon tree species, height, and trunk diameter variables. Since the sampling pattern used by the scientists results in quite a bit of blank space in the scene, we also include randomly placed billboard trees in the style of architectural models to indicate uncertainty in the data in these sparse regions. Interaction with the 3D view is done through physical rotation of the device, looking up to playfully experience the forest as in Figure 1, or looking around to more seriously analyze the distribution of tree species, heights, and growth, decay, or harvesting over time. As the 3D view is rotated, the glyph-based visualization in the linked 2D view rotates correspondingly so that the two views stay in sync.

### **4.4 Linked 2D View and Interaction**

The 2D view consists of a glyph-based multivariate visualization, like a map of each tree in the plot, but where the icon for each tree is a glyph that encodes 6 data variables for each tree. These additional data help scientists to understand the carbon content of the forest and develop estimates that are used to make climate policy decisions. There is also a data legend and interactive timeline. Interaction with the 2D view is accomplished via multi-touch input (Figure 2). The map can

be translated, rotated, and zoomed. These interactions immediately update the linked 3D view so interaction with the map serves as a VR navigation technique. Touching the timeline at the bottom changes the year of data displayed.

## 4.5 Outlook and Conclusion

We believe the current prototype is useful to report to the visualization community because the low-cost makes it widely accessible, and the linked-view VR technique could be applied to so many different visualization scenarios. These include: (a) brain imaging where neurosurgeons benefit from stereoscopic 3D displays but often wish to also see complementary slice-based data because they have trained to understand the brain anatomy using slices, and (b) immersive analytics where the abstract data presented in stereoscopic views can be usefully filtered using 2D interactive parallel coordinates and related plots.

In this chapter, we can see that off-the-shelf mobile devices are powerful enough to facilitate interactive exploration of spatial 3D data, but the exploration capabilities should be limited to account for computation capabilities of these mobile devices. Even with the reduced flexibility, the visualization could well be suited for public-facing visualization use-cases.

Even though this work provides accessible options for exploring scientific data, it does not provide means for data collaboration. Therefore, users are in isolation, making impossible for them to ask questions and share findings to others. This might be an acceptable approach for one time usage but not for classrooms or team-science. In the next chapter, we will go over a project that brings various platform-specific solutions into one visualization framework that enables users from various backgrounds to collaborate in a team-science project.

## Chapter 5

# Everyday Communications

### V-Mail: 3D-enabled Correspondence about Spatial Data on (Almost) All Devices



Figure 5.1: Three working platforms that demonstrate different platform fidelities of V-Mail for analyzing Antarctic ice-sheet data.

### 5.1 Introduction

In this chapter, we focus on the third research component *Everyday Communications* and on supporting collaboration across different visualization approaches—1) high-end but with computation requirements and 2) lightweight but with limited flexibility—to cover a wide range of use-cases for collaborative discussion of 3D data analysis. We introduce cross-platform applications, interactive techniques, and communication protocols for improved multi-person correspondence

about spatial 3D datasets.

Spatial data visualization has long been essential for breakthroughs in medicine, science, engineering, the humanities, and more (e. g., [61, 10, 120, 1]). Sharing these visualizations with others, however, remains a major challenge for many 3D, scientific, and/or big data visualization applications because they typically require high-end devices and data processing—the type of computing infrastructure that is not portable and not accessible to most non-experts. The tools typically employed in data analysis, moreover, often do not support a flexible export of visual results, other than in the form of static images and, maybe, videos. The resulting inability to bring this type of spatial visualization outside of supercomputing centers, laboratories, and other high-end workplaces is a big problem because it stops us from including more diverse groups of people (e. g., citizen scientists, affected patients) and, often, even our own team-science collaborators in the data analysis.

One strategy for addressing this problem is to port the exploratory visualization tools scientists use on their current high-end visualization systems (e. g., advanced volume rendering) to the commodity devices that people use regularly, such as through remote rendering [77] or graphics shaders adapted to work on lower-power devices. Exciting research is being done in this space and, as networking and computing hardware improve, these approaches are increasingly practical. A fundamental limitation, however, is that, as hardware improves, scientists ask even more complex questions or demand more detail, requiring ever more complex data storage, processing, and visualization to address. We are thus always likely to see some disconnect between scientists’ high-end visualization tools and the commodity solutions in our offices, homes, or pockets.

In light of this situation, we take a different, complementary approach. We argue that bringing full-fetched data exploration capabilities to every device may not be the best way to address the problem of high-end collaborative visualization for spatial 3D data, but we should rather improve *human-to-human communication* about the data using everyone’s devices. This approach conceptually builds closely on prior work in storytelling with data visualizations [62, 26, 92], which has been explored extensively for 2D abstract data but less so for spatial 3D data,

and on intelligent image-based viewers of supercomputer simulations/visualizations [107, 4], which preserve some ability to explore data visualizations outside of a native high-end 3D graphics context but do not yet include specific support for collaborative data annotation etc.

To fill this gap in the current visualization toolset, we introduce our V(visualization)-Mail framework to address three specific problems in collaborative spatial data analysis:

First, most current tools are for experts only. V-Mail addresses this challenge by adopting a keyframe-based storytelling metaphor that builds upon prior work in data stories [119, 5]. Since a storybook metaphor is already well understood by users, the V-Mail framework focuses on extending this concept to work with 3D data. V-Mails include not only static data views captured directly from an exploratory visualization but also the contextual animations that are required to maintain spatial correspondence when “turning the page” to a new view. The captured data views are represented as 3D frames floating in the same space of an exploratory visualization, enabling the audience to see these from various vantage points, helping them understand their spatial correspondences to underlying data and other captured data views. The floating 3D frames also work as story navigation widgets for quickly revisiting a point in the story for verification and further investigation.

Second, current tools that support exporting to lightweight formats—imagery or video of which we may think as a form of “data story”—treat this feature as a one-way, one-time export so there is no ability for collaborators viewing these exported media to further explore the data and add annotations/insights back into the data analysis system. V-Mail addresses this issue by treating the data-stories as “living documents” for interactive storytelling and bidirectional communication, where the audience for an initial story can further explore the views and data visualizations depicted in the story and can also quickly become co-authors, adding to the story. Any information added by these co-authors remains connected to the original data so that any new views, annotations, etc. added by co-authors are available in the original visualization software.

Third, most current tools require collaborators, who together wish to explore spatial data visualizations, to be co-located or to all have access to similar high-end hardware with advanced support for computer graphics and/or data processing. V-Mail addresses this problem by using an URL of a standard video file as the base ‘token’ for distributing a data story. By packing the communication about the data into a standard video format and sending this critical human-to-human communication rather than the raw data and visualization application themselves, V-Mail leverages existing e-mail and social media applications as tools for distributing stories. A single V-Mail story token can trigger experiences with different fidelities, based on the capabilities of the current device. Anyone with a video player can at least passively view the story, including annotations made by others. Yet when loaded into one of the dedicated V-Mail clients, the URL of the video file acts as a key that unlocks additional capabilities. In the highest-fidelity case, the token unlocks data on a V-Mail server than can be loaded via a plugin for desktop-based visualization applications, where users can explore and annotate the 3D data more deeply.

In summary, the main contributions of this chapter are:

- the design of a novel visualization framework to facilitate 3D-enabled multi-person correspondence about spatial datasets for both team science,
- an extension of keyframe-based storytelling metaphors to account for 3D spatial data, especially the challenge of maintaining context during transitions and facilitating exploration at a given view,
- interactive techniques and story data formats to support co-authorship, treating the created 3D data stories as asynchronously collaboratively authored living documents,
- the design of a data story server and communication protocol for using V-Mail across an ecosystem of hardware platforms that seamlessly adapt the fidelity of the experience to the hardware, and
- user feedback and lessons learned from a first evaluation of using V-Mail in

a real team-science setting where team members utilized all V-Mail client platforms we created (desktop app, mobile app, and native video players on multiple mobile and web-based devices).

## 5.2 Related Work

V-Mail relates to research on interactive tools, techniques, and formats for storytelling with data visualization and builds upon multiple topics (e.g., animation and annotation, interactivity, co-authorship and collaboration) that have become consistent themes in this research. We note that, although storytelling techniques have been used for presenting both spatial [119, 82, 108, 78] and non-spatial [102, 70, 34, 96, 69, 7] data, recent work has focused more consistently on non-spatial data. V-Mail, therefore, builds upon a trend of customizing storytelling support tools for specific types of data (e.g., [76, 119, 5, 106]), but does so for the specific case of spatial 3D data, as often encountered in domains such as physics, astronomy, biology, and medicine.

### 5.2.1 Co-Authoring and Interacting with Stories

Most often, we think of stories as an end result—the final outcome of a visualization process used to convey insights to others. Research suggests several benefits, however, to adopting a broader conception, one where software systems are designed to help capture and present stories iteratively throughout the data analysis and/or visualization process [82]. Some tools enable users to build stories from *both* data views saved during previous analysis and new views created in real-time during interactive data exploration [42, 5, 119, 78]. V-Mail adopts a similar philosophy where storytelling with data exploration are tightly integrated and stories are shared within a team and refined iteratively.

In this way, V-Mails should most often be thought of as co-authored, falling somewhere in the middle of the spectrum that Segel and Heer [96] describe, which ranges from author-driven to reader-driven approaches for consuming data stories. Traditionally, stories are told in the author-driven approach, with predefined



sequencing and messaging determined by the authors and no interactivity (i. e., like in a book). On the other side of the spectrum is the reader-driven approach, where viewers freely explore a data visualization. Some researchers argue that this extreme should not be considered data storytelling since it does not contain any message from authors [102]. For the purposes of this chapter we interpret storytelling broadly: our fundamental interest is in multi-person communication, not just after discoveries are made but also as science is developing within a team.

Many forms of storytelling are, by nature, collaborative activities [64, 70, 123] and people often take on different roles in this process [70, 23, 40]. In a recent survey, Tong et al. [108] describe authoring tools for parallel storytelling, where multiple authors work simultaneously to create the final visualization content. Like V-Mail, this type of storytelling blurs the lines between storyteller and audience; the audience partakes in the storytelling and the initial storyteller is also an audience member. In sense.us [42], e. g., users communicate collaboratively using annotations and comments posted online on web-based data representations. In GeoTime [27], the audience partake in the storytelling process. In an accompanying text editor, authors write text-based data stories using bookmarked data views as references to claims. By scrolling the editor filled with the links, the audience has the ability not only to see the message with text descriptions but also to flip through saved visualization states for further exploration. And also by modifying text in the editor, the audience can add new content or even new data views found in their own data analysis sessions.

V-Mail is similar to GeoTime in that multiple users collaborate on visualization presentations. Unlike GeoTime, however, V-Mail employs several simple yet effective techniques to convey different users' contributions. As done by Heer, Viegas, and collaborators [42, 114], e. g., each comment shows the author of the edit, and the last editing time is visible on a corresponding message. Further, V-Mail incorporates lower-fidelity options for viewing and collaborating with others on low-cost devices such as mobile phones. By sharing a visualization state via a URL [42, 114], V-Mails can be referenced in other communication media such as personal blogs. Similarly, by using video files as the means of distribution [48, 5],

V-Mails can be widely distributed, including through social media. In V-Mail we provide users with different options for consuming data stories, from passive viewing to interacting with them, as there is no one correct level of interactivity on the spectrum for constructing a narrative visualization [40, 82, 102]. While interaction can distract viewers from an initial story arc [64], the ability to interactively view data stories is typically seen as giving the audience a feeling of involvement and to lend credibility to the messages told [82, 119, 78, 123, 65].

In practice, the intended hardware platform for disseminating the story often determines the level of interactivity of the story. If the audience has access to the same (often high-end) hardware used to store and/or analyze data via an exploratory visualization system then the easiest approach to supporting interactivity is often to tell the story within that same exploratory visualization tool because all visual representations are supported by the existing hardware. The visualization tool can then be extended to include story elements, while taking advantage of the interactive exploration features already provided by it [119]. Of course, this approach can severely limit the accessibility of the story due to the required hardware (and its limitations). To free storytelling from such hardware limitations, one can create stories to be viewed interactively on a web-based exploratory visualization system (e.g., [106, 114, 42, 78, 23]). Even though this approach supports almost any device (with a browser), this only works if the visualization techniques can be implemented within a browser environment, which is not the case for many spatial data visualization systems that are often built as standalone applications such as based on ParaView. An alternative approach is to export the story as a video [48, 5], which makes it widely accessible but does not support interactivity. Striving to find the right balance, researchers have also developed innovative techniques, such as “explorable images” to support a surprising amount of interaction with large datasets on low-power devices [107].

With V-Mail we essentially combine all of these strategies. We use a video that can be viewed on almost any device, while also supporting a range of higher-fidelity clients that support additional interactive data exploration. Together, these devices form an “ecology,” allowing users to pick the device best suited for

their use case. In a similar spirit, Jeong et al. [52, 53] support desktop and large touch-enabled displays to promote both individual and group collaborative tasks in data visualization. Their system, however, aims at synchronized collaborative scenarios, whereas we designed V-Mail for asynchronous communication.

### 5.2.2 Annotating Spatial 3D Data

When compared to creating data stories for 2D or non-spatial data, authoring stories about 3D spatial data includes another special consideration in that it requires connecting text, speech, drawings, or other input from authors to specific spatial views or data elements. These software features are often described as 3D annotations, which can be tied directly to data objects [119, 110]. Alternatively, graphical annotations can be drawn in ‘screen-space’ [5, 42, 110, 76]. Without the need to explicitly reference data elements, this ‘screen-space’ drawing with ‘free-form’ annotations enables users to be more expressive [42] and even to draw in ‘empty space,’ which can be useful in sparse 3D scenes [110]. However, free-form ‘screen-space’ annotations are typically not useful when viewed from other vantage points, as the spatial context is only valid from the exact viewpoint where the annotations were made. Some form of navigation between annotations is thus needed, and it is also useful to be able to see what viewpoints include annotations. V-Mail thus implements screen-space annotations in the style of Boom Chameleon [110]. After creating an annotation from one viewpoint, we add a snapshot of the annotated view to the scene as a 3D widget (view frustum with a textured film plane) that can be seen from other vantage points and returned to later.

### 5.2.3 Arranging and Transitioning Between Multiple Views

Many data storytelling systems provide multiple complementary data views, and they are considered critical for 3D data storytelling [108, 5, 119]. One reason is that understanding the complex spatial relationships in 3D data often requires multiple and/or animated perspectives [64, 82, 74, 102]. Animations can visually transition continuously between them to allow the audience to build a congruent

mental model of the spatial data [34].

Different mechanisms exist for authoring animations for data storytelling. These can be as simple as recording a sequence of interactions performed by the storyteller [119] or providing animation templates to assist users in creating a final animation [5]. Authoring a meaningful animation, however, can be complicated. Automated techniques are thus also useful, especially in time-critical scenarios such as urgent care in a hospital [48] and even for science dissemination [65]. V-Mail, adopts a semi-automatic approach as the one by Lidal et al. [76], where we create animations by interpolating values the storyteller has captured/created in discrete states.

V-Mail animations are based upon “keyframe visualization states” defined by the user, and animated transitions between these are computed automatically. Since each discrete state provides a context for multiple users to annotate or comment on the data, they support a style of communication that is similar to the web-based sense.us 2D visualizations. However, V-Mail’s keyframes include camera parameters that associate them with a specific 3D spatial context. We use animations to transition between these camera (and all other visualization) parameters recorded in each keyframe state, and the system automatically uses a staged animation [41, 5] to increase clarity when the transition would require changes to several parameters at once.

When storytelling with non-spatial data, there is potential to use spatial layout as a way of encoding the sequence of a story, for example, by taking advantage of people’s natural reading direction [64] and learned conventions [8, 126]. Since this is not often possible with 3D spatial data, V-Mail includes a linked 2D storyboard view to define the temporal context for each key state and to re-sequence the story if desired. This feature is motivated by prior work that created guided 3D visualizations by capturing and ordering multiple views and found that breaking the presentation into steps can improve comprehensibility [119]. With timeseries data, it can be useful to arrange such steps according to the time series (e.g., [66]), but tools that support different progressions are most flexible in storytelling (e.g., [119, 5]), sometimes even supporting a sequence of content categories (e.g.,

[96, 45]). As in other flexible story authoring tools [5, 42, 119], V-Mail authors are able to organize views in any order to create animations that convey spatial relationships, show evolution over time, and/or generally overcome the uncertainties that can be present when viewing 3D data using a single image [34].

### 5.3 Design Criteria and Core Design Concepts

Based on this discussion of existing means for communicating about or using spatial 3D data and the challenges we outlined in the introduction, we now translate these points into specific design criteria and introduce the design concepts of V-Mail that guided us toward our vision.

#### 5.3.1 Design Criteria

Our overall approach is driven by today’s huge spectrum of data communication possibilities, yet with no individual solution according to our vision. On the one end of the spectrum, people use e-mails enriched with screenshots from general-purpose visualization tools such as ParaView [3]. This has the advantage that one does not have to worry about the device of the addressee, yet messages are limited to texts with few images, with little expressiveness. Video exports—although being one-way means of communication as noted in the introduction—can also be used to showcase visual representations with higher fidelity and in a continuous fashion, yet they are often huge and embedding them in e-mail is less well supported. Moreover, communication features such as drawing and commenting are typically missing in an e-mail based communication. The other end of the spectrum is marked by storytelling tools as the one by Wohlfart and Hauser [119], in which recipients can load a shared visualization not only to view but also to explore. Unfortunately, such tools require collaborators to have a similar hardware and software setup and often hours of training to use the visualization application—and thus are often limited to experts as we argued before. Our key goal is thus to facilitate communication about spatial 3D data without having to

worry about recipients' devices and skill levels, yet with a similar ease of communication, responding, and commenting as with e-mails. To achieve this vision, we formulated the following design criteria that are based on ongoing data visualization research on storytelling, communication, and collaboration:

- C1 Audiences have different goals and needs. We thus need to provide them with different options for consuming the presented material, e. g., with different levels of interaction and detail [40, 70, 123].
- C2 Decision making in a group often takes multiple iterations of exchanging ideas back and forth. The exchanged content in a group discussion should therefore be editable and extendable [70].
- C3 In asynchronous collaboration, users can receive messages from others in many situations. We thus want to support a wide range of devices to view messages and provide feedback [53].
- C4 In addition to the final proposal, it should be possible to capture the scientific reasoning behind an interpretation and communicated it to others to help them make informed decisions [76, 119, 83].
- C5 Creating a visual presentation about spatial 3D data is a creative process. Presenters should thus have various options to express their ideas and thoughts [76].
- C6 When going through the steps of presenting spatial data, it is important to provide means for the audience to maintain spatial correspondence as the presentation proceeds and to understand where in the data each step is showing [108, 82, 110, 65].

### 5.3.2 V-Mail Core Metaphor and Design Concepts

Storytelling at its very core comes from stories that have been recorded, since Gutenberg and the Grimm brothers, in books. Let us take such a book as the basis of our metaphor—specifically a children's picture book with some text on each page. Those books are communication media that enable readers to consume a story in a series of steps, at their own pace. A child looks at a page in the book

and is read the text, to explore the episode in the fairy tale or to understand a concept in a nonfiction book. To advance, the child *flips to the next page* to continue to the next episode in the tale or to the next concept. We can extend this metaphor to ‘regular’ books, only that the function of the page in the children’s book is now served by a section of text within a chapter. We can also extend the metaphor to the *concept of chapters*, in which one train of the story changes to a new one, whose relationship to the first may not immediately be apparent. Moreover, books easily lend themselves to annotations in various forms, such as drawn illustrations or written remarks in the margins.

With V-Mail we take this metaphor and apply it to the visualization of spatial 3D data. A ‘page’ is a **view of the 3D dataset** that shows a particular situation. Annotations can be provided by **sketching** onto the 2D projection of the 3D view or by attaching textual annotations to the view. ‘Flipping to the next page’ then **animates from one 3D view to the next**, allowing the viewer to follow along without losing the spatial context. Several page flips can be connected into ‘**chapters**,’ where a new chapter would start with a new view yet without an animation leading up to it. Like with the picture book that drove our metaphor, we can envision to animate **forward and backward** through the data story, allowing viewers to navigate it and to add to or to adjust it. Using this approach, complex messages can be broken down into more digestible, visual, and expressive forms (C4–C6). In addition, we extend the V-Mail framework with three additional concepts as follows:

**Floating 3D pages**—When presenting visualization results with a set of captured data views, we often think of a panel listing the views; e. g., thumbnails on the viewer in AniViz [5]. In V-Mail, in addition to this panel, we spatially place and visualize the data views in the same underlying 3D data to show the user how the views are spatially located within the data. Together with the smooth transitions between the data views through animations, the floating pages then allow the user to maintain spatial correspondences between the data views as the user gradually progresses through a data story (C6).

**Living documents**—To remove the one-way character of existing 3D data

communication, to turn the data communication into a collaborative and iterative process, and to allow users to extend the communication to non-experts, we created V-Mails as living documents (C1, C2). To realize this vision, we allow users to explore V-Mail, provide annotations, and extend stories regardless of their background and used platform, to the degree their device supports such input.

Communication via a **lightweight token**—To realize this device flexibility (C3) and thus be able to address a broad audience (C1), we do not rely on dedicated rendering support. Instead, we share stories as a video URL—online token that can be interpreted based on the used device and the absence or presence of dedicated software. For instance, a low-fidelity version of the data story could allow users to open it on a mobile phone with a video player, for instance while traveling. A higher-fidelity version that requires a dedicated software would then offer additional exploration and annotation capabilities, even on mobile devices. On a high-end desktop, users can then freely explore the data depicted in the story and add additional pages or chapters. To make it easy to manage such device flexibility, we embed all story data into the video, and share it as a V-Mail URL token that is opened appropriately by the different devices.

## 5.4 Detailed Design and Implementation

Based on this metaphor and the mentioned concepts, we now describe the visual components, interaction techniques, and distribution mechanisms that help us to realize our vision.

### 5.4.1 Visual Components

A V-Mail story is composed of data views with drawings and comments from different users. We add animations in-between the data views to convey their spatial correspondences in a continuous fashion. Our V-Mail desktop client is one example of a V-Mail client (Section 5.4.3) and is a plugin to an exploratory visualization application [55]. It allows people to create and view this story and comprises three visual components: (1) the storyboard, (2) floating 3D data views,



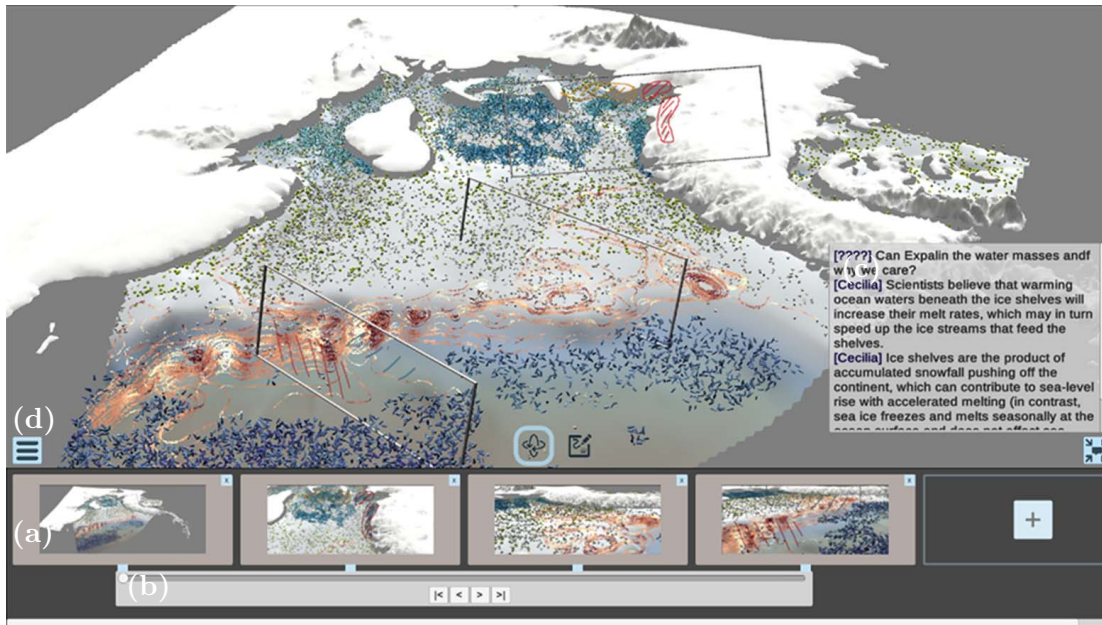


Figure 5.2: The V-Mail desktop client allows users to create a story directly from a data visualization application: (a) captured *data views* on the storyboard panel; (b) the *timeline* interfaces offers different playback options and indicates the current time in a story; (c) the *comment panel* shows comments left by others on the current data view; (d) the *drop-down menu* provides options for opening, uploading, and sharing a story.

and (3) animated-transitions. Each component visualizes different information associated with the story.

### The Storyboard with the Comment Panel

This first visual component shows an overview of a data story and the input from contributors (Figure 5.2). *Thumbnails* of data views provide a quick glance at important points in a story and its presentation order. We also overlay *drawings* on the thumbnails to indicate visual highlights from users. Sometimes it may be more appropriate to textually describe what is shown in a shared data view; e. g., for writing a case number in a data ensemble or the name of a rendering algorithm.

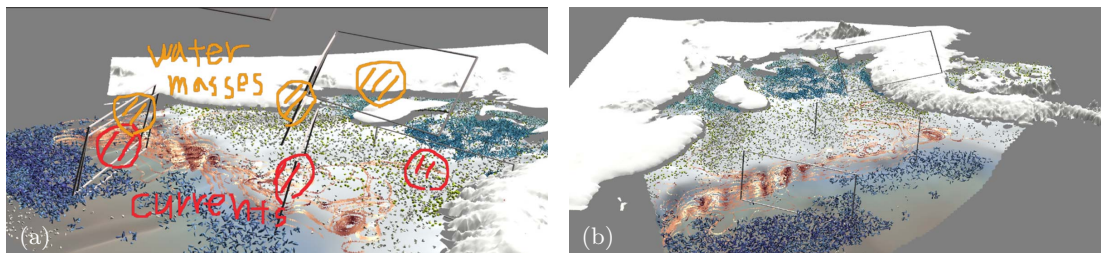


Figure 5.1: Example usages of 3D data views in data communication: (a) the user talks about data features focused in the views; (b) a bird’s eye view shows the locations being discussed in the data.

The *comment panel* provides an interface for leaving such notes and viewing comments left by others (Figure 5.2(c)); each comment includes the respective user’s name to differentiate authors of each content.

### Floating 3D Data Views

This second visual component shows the user how the story is spatially located in the 3D data space. As shown in Figure 5.1 and inspired by Tsang et al. [110], we place captured data views into the same space as underlying data visualization. This 3D view makes the captured data views visible from other vantage points, allowing users to associate this view with other parts of data (even the parts that were not initially shown from the view). For example, a shot could have been taken close to a particular feature, after which the user zooms out to see where the shot was taken by observing its placement and viewing direction in context of the whole data. By making this spatial information visually explicit, users can also visually reference other data views from the current view: a shot can show adjoining data views to convey their spatial relationship, before transitioning to each view to describe each in detail (Figure 5.1(a)). We can also convey a spatial overview of activities in a data analysis session: by showing the data views scattered around visualization, from a bird’s-eye view, user can get a sense of locations of the interesting points in a data analysis session (Figure 5.1(b)).

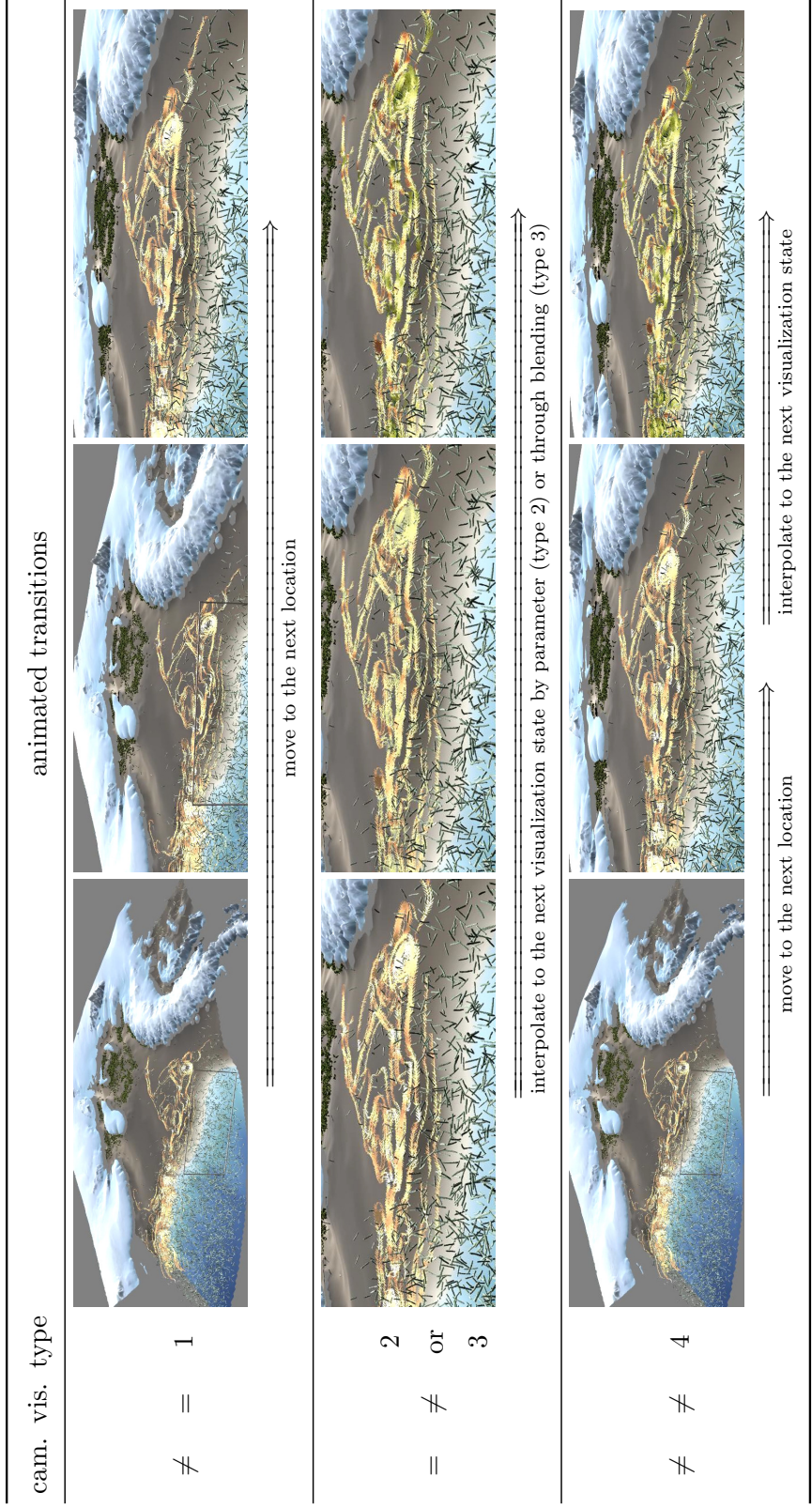


Figure 5.3: Different animations to transition from one data view to another. Each type shows what we change in between two adjacent data views.

## Animated Transitions

With this last visual component we convey spatial and contextual correspondences between data views in a story. Instead of flipping through separate data views, we use animated transitions between data views so that the audience can gradually adapt to the visual changes in different data views. We automatically create animated transitions whenever a new data view is added to minimize the time and cognitive effort needed to create a V-Mail story.

There are four types of animated transitions (Figure 5.3), which are used depending on the differences in values of view information and visualization states captured by adjoining data views. If only the camera location changed, we (1) use a camera transition to convey their spatial correspondence, which transitions the camera from a previous location to the next location.<sup>1</sup> When only the visualization state has changed, we can (2) gradually change the values of visualization parameters from the previous state to the next by interpolating the values of changing visualization parameters. This option enables users to stop the transition anytime and explore the visualization in an intermediate frame, but this exploration is only possible when the set of visualization parameters of two states are the same and the parameters can be changed continuously (e.g., changing a slicing plane in volume rendering). In cases where there are no obvious intermediate frames (e.g., changing a visualization type or dataset) we (3) use an image-based blending approach. This blends two images where the screenshot from the previous data view fades-out and gradually fades-in into that of the next data view (see the second row of Figure 5.3).

When both camera location and state change, we (4) break the transition into two stages. We first move the camera to the next location and then gradually change the visualization state to that of the new data view (see the last row of Figure 5.3).

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<sup>1</sup> In our prototype we use a linear camera motion between two locations. Nonetheless, other kinds of camera animations and criteria to determine the differences between two states could be more useful. We thus implemented the animated transitions as abstract methods to enable future developers to override default animations with new ones that may be more suitable for other situations.

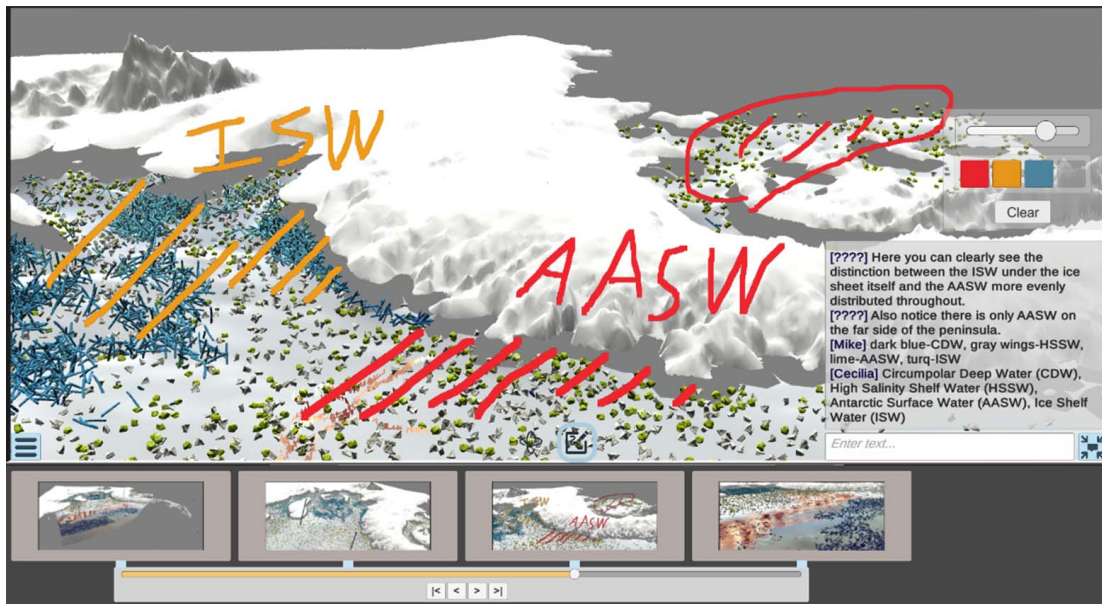


Figure 5.5: The user sketches and leaves comments on the current view in the annotation mode. A drawing pallet is for specifying the color and the size of a brush. Clicking the toggle on the top of the storyboard switches the current mode to the exploration mode.

#### 5.4.2 Basic Story Interaction

To create, view, and explore V-Mail stories we also provide dedicated interaction techniques, as we describe next.

##### Creating a story and annotating data views

We begin creating a story with an empty storyboard. Users can navigate in the data visualization application (in the 3D view; Figure 5.2(d)) using typical 3D view manipulation techniques, and then add a chosen data view to the storyboard via a dedicated button (“+” button in Figure 5.2(a)). We then capture a thumbnail of the view and insert it as a reference into the storyboard (Figure 5.2(a)), also extending the timeline (Figure 5.2(b)) appropriately (for  $\geq 2$  thumbnails) to account for the needed transition animations. Users can also re-arrange the data view sequence using simple drag-and-drop interaction and remove data views as

desired.

To be able to tell a story effectively or to respond to one, it is also often useful to sketch directly on a view to direct someone’s attention to particular features, which we support on captured data views (Figure 5.5). To avoid conflicts between sketching and view manipulation, we differentiate explicitly between these two modes and users can switch between them using two buttons at the bottom of the data view. In addition to the sketches, also longer textual comments can be left for each captured data view (Figure 5.2(c)).

### **Uploading a story**

Once done writing thoughts down on the data views, the user can upload the story to a server to share it. Instead of uploading a story to the server whenever there is a change, we initiate this upload process explicitly (via an entry in the drop-down menu). We chose this design to enable the user to ideate and draft a story before sharing it to others, similar to drafting an email before sending it. This way we also avoid a constant client-server communication which, in contrast to e-mails, can be heavy as we describe in more detail later.

### **Viewing an animated data story**

As a sequence of data views with animated transitions in-between, a V-Mail story is akin to a video with chapters. We thus borrow different playback modes from traditional video players and adjust them to our application (Figure 5.6).

Like with normal video players, we support a normal playback that continues until the end of a story (top row in Figure 5.6). Different from normal videos, however, we briefly stop at each ‘chapter mark’ to allow the viewers to understand the created data views, and to realize that a new animation follows. To better emphasize the data views we also provide means to only animate to the next view to then be able to explore it further, read annotations in detail (second row in Figure 5.6), or to be able to respond to them—similar to the playback style used by Wohlfahrt and Hauser [119]. Finally, for faster navigation we also support

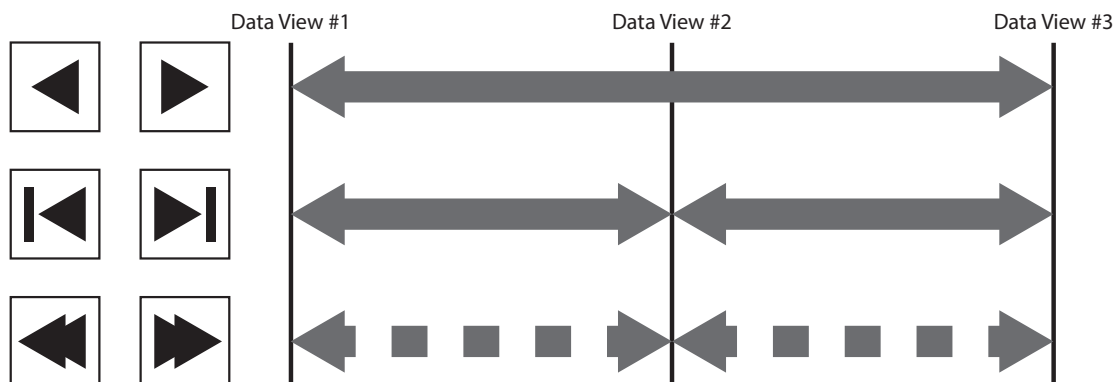


Figure 5.6: Playback options & corresponding buttons. Top: plays the animation from start to finish, or in reverse; middle: plays it until it reaches the next/previous data view; bottom: jumps to the next/previous data view.

flipping between data views without animations (bottom row in Figure 5.6).<sup>2</sup> Another aspect of data stories that is different from normal videos is that in our stories we do not have to insist on always having to animate from start to finish—it may also be meaningful to watch a single transition or the whole story backward, and we thus add the respective reverse navigation means for all three of the play modes.

To allow users to explore V-Mails in a more fine-grained manner, similar to video players we also provide a timeline slider (Figure 5.2(b)). To emphasize the aspect of chapter transitions we constrain the timeline dragging to between two neighboring data views, so that it is easy for a user to focus on the visualization view while controlling the timeline with a mouse. This constraint is reset on each mouse down (for exploring a new transition) and can be fully lifted with a modifier key to explore the entire timeline in one go.

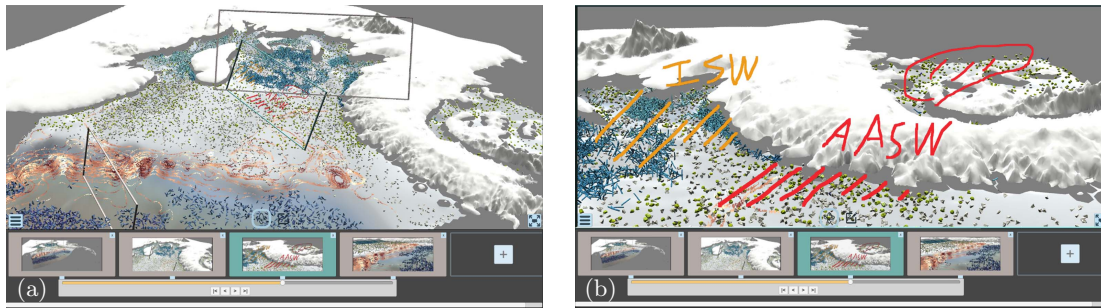


Figure 5.7: The data visualization application and the storyboard are visually and interactively linked. (a) by hovering over a 3D data view frame in the 3D view (the center one here) highlights the frame and its corresponding thumbnail on the storyboard; (b) clicking on this data view frame in the 3D view makes the storyboard jump to this data view.

### Linking free exploration and storyboard timeline

Again different from traditional video players, the interaction in a data story is not restricted to just playing back a pre-created video stream. Instead, a user may go back to freely exploring the 3D data visualization, potentially to capture slightly different shots or to better understand a given representation. Similarly, after such a free exploration (and if no new shot was added to a timeline), the viewer may want to transition back to the timeline. We support both of these type of transitions by keeping the 3D visualization view and the timeline exploration linked, and realize them through animations from the set described in Section 5.4.1. Each time a user switches from timeline to 3D view, we store the current position in the timeline to be able to transition back. In the opposite direction, we create a transition from a current state in the 3D viewer to the last active one. We also allow users to jump to stored data views not only by interacting with the storyboard view but also by clicking on the respective data view frames in the 3D view (Figure 5.7).

<sup>2</sup> The desktop client does not have these skip buttons because the skipping navigation can be done by clicking thumbnails (Figure 5.2). In the mobile client, however, we place the buttons in the bottom corners of the display to provide easier access with grabbing hands (Figure 5.9).



### 5.4.3 Cross-platform Collaboration Mechanisms

To truly support our cross-device collaboration vision (C3) we cannot rely on all users having access to a high-end PC like it is required for the interaction so far—at least not at all times. We thus now describe how we enable users to respond to V-Mails on different devices and then introduce platform-specific prototypes (i. e., V-Mail clients).

#### **Flexible export of data story**

As we want to support a wide ecology of devices, we have to ensure that they can show a V-Mail without advanced rendering hardware and even potentially without a dedicated client. As a most basic representation we thus rely on a traditional video that we generate from the data story, just as if one would have used a normal playback to watch it. Any device that supports video file playback (we use MP4 files) can thus show this most basic V-Mail format—including virtually all mobile phones, tablets, and laptops. Devices or players that also support video subtitles embedded in video files can also show the textual comments. Similarly, we also embed chapter marks for those video players that support it.

If a person receives V-Mails on a more regular basis, they can decide to install a dedicated tool that can enable them to further engage with V-Mail. In this case we provide access to the dedicated play modes we described in Section 5.4.2, and for this purpose also include a video file exported in the reverse direction. We also allow users to adjust or add to the graphical and textual comments. To allow users to edit the comments, we save both types as separate files (i. e., different from the video), that can be updated by the dedicate player after a change.<sup>3</sup> In addition, we allow users with dedicated software even on low-power devices some simple ‘3D exploration.’ As we cannot rely on rendering hardware, we use 360° images that we create during story export for each of the data views. We also store additional information in JSON files that allows us to switch between the different interaction modalities.

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<sup>3</sup> Users who only use a regular video player would not see such a change, this would only be updated after another full export.

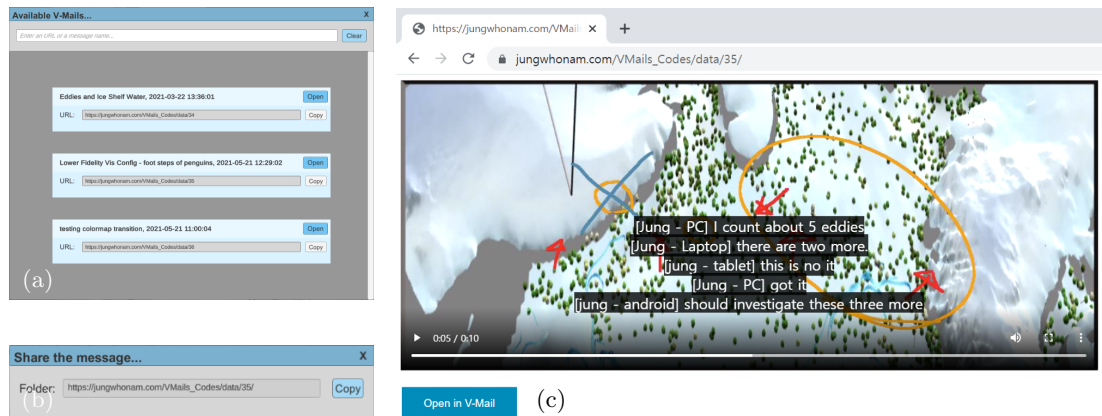


Figure 5.8: A story URL works as a lightweight token for sharing and opening the story. (a) our V-Mail clients show several stories with their URL; (b) after a story's upload, the client shows the URL; (c) opening the URL takes the user to a webpage where the story video can be played and the story can be opened in a dedicated client via a button (bottom).

For users with sufficient high-end hardware and the full visualization software, finally, we naturally also store all data views, camera locations, and visualization states. Only with this data it is possible to adjust the data views, add new ones, rearrange their sequence, and re-export an updated story.

### URL as a lightweight token for story sharing

While we export a collection of files for each story, we do not want to bother users with having to manage and send these files. We thus manage the file collection on a dedicated server (that only has to provide file management and remote access) and instead share a story in form of a URL that points to the repository. An essential benefit of using a URL is that this allows users to not only link to a story in an e-mail but also to share a story on social media. We create this URL after each export (Figure 5.8(b)) and, when opened in a web browser, simply shows a video player (Figure 5.8(c)). On devices with access to our dedicated clients the website also provides a means to open the story in the dedicated software. Alternatively, the clients also provide a list of stories stored on the server (Figure 5.8(a)). In

both cases, the clients then access the files needed for their specific capabilities and provide the respective interaction tools, as we detail next.

### **A device ecology for collaborating on data stories**

We implemented three specific clients as a proof of concept, which mirror the data levels we described in Section 5.4.3. In Figure 5.1 we show photos of these solutions and in Table 5.1 we compare them by the features they support.

As just described, our most basic **web client** relies on the video player available on virtually all connected devices (Figure 5.8(c)) to facilitate passive storytelling [119]. Depending on the functionality of this player, one may only perceive the story as a simple playback with graphical annotations for the data views. If the player supports it, however, one may also jump between chapters and/or see the textual comments that are available as video subtitles.

The web client can be accessed on virtually any connected device and uses the device's built-in video playback. With it we can thus reach completely new audiences with data stories. Even if someone never used a data story before and thus does not have or is not willing to install dedicated software, they can still view them. Depending on the media channel used to share the URL, they can also respond to a story such as by commenting in a separate e-mail. Moreover, this form of consuming also allows users to explore the story on their own [70] first, before potentially becoming more engaged to be interested in a closer collaboration.

In that case they may accept to have to install a dedicated tool, such as a **dedicated mobile app** on their phone or tablet. We realized this client as an app on Android (Figure 5.9), allowing us to provide a higher fidelity of interaction for both phones and tablets. On top of only playing back the video of the data stories, our app also allows users to make use of our advanced playback modes, add new annotations (both graphical and textual, whose updates are re-uploaded to the server), and have limited 3D exploration via our pre-computed 360° images for each data view. As it is likely used on small-screen devices and does not facilitate changing the chapter order, instead of using thumbnails for the data views in the storyboard we place crumbs on the timeline to provide visual and navigational

Table 5.1: Availability and fidelity of operations that facilitate collaboration around shared stories and their prerequisites, by client/platform.

	<b>web client:</b>	<b>mobile client:</b>	<b>desktop client:</b>
<b>traditional video player</b>		<b>custom video player</b>	<b>plugin to vis. tool</b>
		— <i>interactive storytelling</i>	—
<b>story navigation</b>	playback and timeline controls without pausing points	playback and timeline controls with pausing points, storytelling affordance that distinguishes story nodes and transitions	
<b>exploration</b>	<b>no support</b> (i.e., passive storytelling [119])	<b>partially</b> (360° views; i.e., storytelling with interactive approval [119])	<b>full support</b> (all four modes of author- and reader-driven storytelling [119])
		— <i>collaboration around shared stories</i>	—
<b>view comments</b>	<b>partially</b> (if player shows subtitles)	<b>yes</b>	<b>yes</b>
<b>view annotations</b>	<b>yes</b>	<b>yes</b>	<b>yes</b>
<b>leave comments</b>	<b>no support</b>	<b>yes</b>	<b>yes</b>
<b>leave annotations</b>	<b>no support</b>	<b>yes</b>	<b>yes</b>
<b>extend story</b>	<b>no support</b>	<b>no support</b>	<b>yes</b> (add, remove, rearrange story)
		— <i>software and hardware prerequisites</i>	—
<b>software needs</b>	<b>none</b>	<b>dedicated app</b>	<b>special visualization software</b>
<b>hardware needs</b>	<b>virtually none</b>	<b>virtually none</b>	<b>high-end GPU &amp; CPU processing</b>

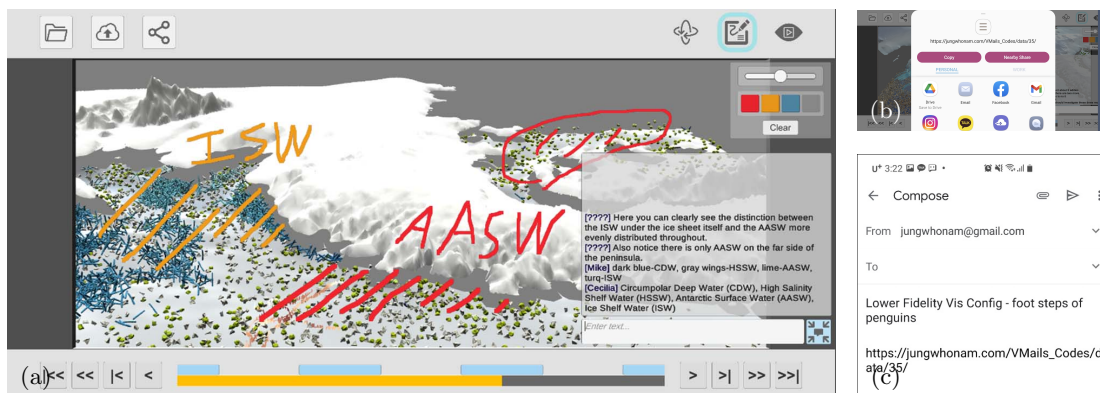


Figure 5.9: We created the V-Mail mobile client (a) as a custom video player with visual components and mechanisms for interactively viewing and editing a story; clicking on the top-left share button in the viewer copies the story’s URL and shows messaging apps to share the URL with (b); when clicking an e-mail app, we create a message with the name of the story as a title and the story’s URL pasted into the main body (c).

support to users.

The mobile app thus facilitates a much richer form of collaboration by means of data stories than the web client, including being able to directly comments within the viewing environment and some 3D exploration. Nevertheless, the mobile app still relies to the built-in video playback available in virtually all devices, thus fundamentally does not have any higher processing or rendering prerequisites than the web client. Also, because it runs on mobile devices, it inherently allows people to engage with data stories like they do with other online media, whether in a break, at home, or while traveling. People who regularly communicate about 3D data are thus now able to do so, just like they are using e-mail and social media in daily life. We thus also support sharing V-Mails to other messaging apps installed on the user’s device.

For full-fidelity interaction, however, we created a **desktop V-Mail plugin** to a data visualization application [55] for both Windows and MacOS. This

setup provides the functionality we described in Section 5.4.2 and requires a high-performance computer, yet provides full flexibility in data exploration, story creation and editing, and we assume it to be available for those people who most actively work on the data visualization or analysis. This setup takes care of creating the sharable data story in the first place, and also makes sure that any updates from mobile app users get re-embedded into the video exports. This environment also supports users in creating story branches, upon whose upload a new sharable URL is created.

## 5.5 Application Case and Evaluation

Since we wished to understand how V-Mail might be used over a multi-week period within an active, interdisciplinary science team and access to such teams is limited, we recruited two such teams that have collaborated with our lab on other projects in recent years. Pre-existing relationships like these are difficult to avoid when evaluating software with expert users and always raise a concern about bias in the feedback provided. This concern is mitigated in our study by the multi-week trial period, which required users to engage significantly with the tool and by combining our analysis of self-reported data with coding and analysis of software logs and back-and-forth communications.

We showed V-Mail over a live video conference to the first science research team, studying fiber tracts in a human brain. Their initial reaction was somewhat mixed; they told us the tool itself is novel and could be useful in presenting findings to a broader audience, but there is no urgent need for such tool for their team-science collaboration. We decided not to deploy V-Mail for a multi-week trial for following two reasons: 1) the team is led by one senior member, a professor, to whom his students report to during their weekly meetings; there seems to be no urgent need for additional asynchronous remote communication tools, and 2) a new V-Mail client would need to be developed to integrate with their current software, since it had been several years since our lab had collaborated with these scientists to visualize the unique brain micro-structure data [28] and the current

V-Mail prototype is for a more recently developed visualization engine.

On the other hand, the second team is composed of multiple senior members from different organizations, and the prototype V-Mail client plugs into one of the visualization engines they use regularly [55]. Their initial reactions were positive, when we showed the tool over a live video conference, and they decided to be part of a multi-week trial and integrate V-Mail into their normal workflow.

This section reports on training, observations, results, user feedback and other lessons learned from this real-world application. A large portion of the reports is from our observations and interactions with the second science research team. However, several discussion points and limitations of our current approach (therefore future directions) were drawn from initial feedback and discussion with the brain science team.

### 5.5.1 Methodology

**Application Context.** The interdisciplinary climate science research team uses a combination of tools, including some of the world’s most advanced high-performance computing (i.e., supercomputer) simulations, to study complex interactions of Antarctic water masses that may explain the global rise in sea temperature. The team includes oceanographers, geologists, computer scientists, a visual artist, and a science writer. Like many research teams today, they place an increasing emphasis on improved communication with the public. The artist and writer have played leading roles in these efforts, and the team has produced five short videos describing the science in the past seven years, all of which were national competition finalists (two won awards as best submissions). One of their recent videos was created with the Unity-based Artifact-Based Rendering (ABR) engine [55]—the same engine used for our first implementation of a V-Mail plugin.

We selected this team to perform a first evaluation of V-Mail because their work requires some challenging, iterative communication about the spatial, time-varying data. The research is part of the Energy Exascale Earth System Model

(E3SM)<sup>4</sup> project, which involves coupling multiple sophisticated computer models together. To accomplish this work, the scientists, who each have areas of specialization (e. g., oceanography, geology, high-performance computing), must communicate effectively with each other about the science as well as with funding agencies, the public, and other stakeholders. To produce an effective video, the scientists must communicate with the visual artist and science writer, who then work iteratively together, connecting again with the scientists as well as with technical experts in data visualization as needed to confirm messaging, gather the most effective video footage, and so on. This communication is primarily conducted through e-mail and video-conferencing, but schedules are busy within distinguished science teams like this one, and opportunities for synchronous video-conferencing with the entire team are typically limited to at most one time per video project.

**Participants and Tasks at Hand.** Since one of our goals was to understand how V-Mail might integrate with whatever data communication work is at hand in a real, research-active science team, we asked the team to use V-Mail for whatever tasks they thought made sense during the two-week trial we had agreed upon. It turned out that the team had just recently completed producing one of the videos mentioned earlier and submitting it to a competition. So, at this moment, the artist and science writer were deeply familiar with the scientists' current motivations, goals, and results. The most interesting communication task at hand was to develop one or more complementary videos to go deeper into certain aspects of the science and provide useful material for the scientists to use in their presentations. Thus, exploring how V-Mail might be utilized to support this work became the primary task of the V-Mail trial, and the two primary users became the visual artist, a professional sculptor and painter for more than 30 years whose collaborations with scientists led her to data visualization, and the science writer, a Ph.D. student in cultural geography.

**Training.** During the first few days of the two-week period, we met individually with the artist and science writer to provide detailed instructions on the

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<sup>4</sup> See [e3sm.org](http://e3sm.org).



V-Mail clients they chose to use and to assist them in their tasks.

**Data Collection.** We recorded qualitative feedback by taking notes from interviews we conducted after the training sessions as well as via questionnaires before and after the two-week period. In addition, we saved each V-Mail that they created and configured the V-Mail clients to log all edits. Questions in the questionnaires and details of our logging procedure are described in Appendix A.

### 5.5.2 Observations and Results

The presentation in this section is organized by the type of data collected. First, we present results from the pre-study questionnaire, which describe the teams' pre-existing communications and related needs. Next, we present quantitative data from the trial period, obtained by examining the V-Mails produced and software logs. Finally, we present our observations from working with users as they first learned V-Mail and results from post-trial questionnaire.

#### Pre-study Questionnaire

Six participants filled out the questionnaire (A.3.1). Two are from the climate science team and four are from the brain team. Although the questionnaires do ask for quantitative data that could potentially be analyzed for statistical significance, the small number of users in these exploratory studies is not appropriate for formal statistical hypothesis testing.

Participants take different approaches for data communication (Figure 5.10). For an urgent matter, participants typically communicate in-person or send email-like messages. When answering a question that could be responded in few words, participants use an email-like tool. However, when it takes multiple steps to explain a concept, they typically use synchronous communication approaches, such as a live-video conferencing tool. This choice was the same for describing spatial features in their data and for public-facing communication. When asked about usages of visuals in emails, participants responded differently. A user does not use emails for sharing 3D visualization results. Another user said that about 70 percentage of his emails contains images with annotations.

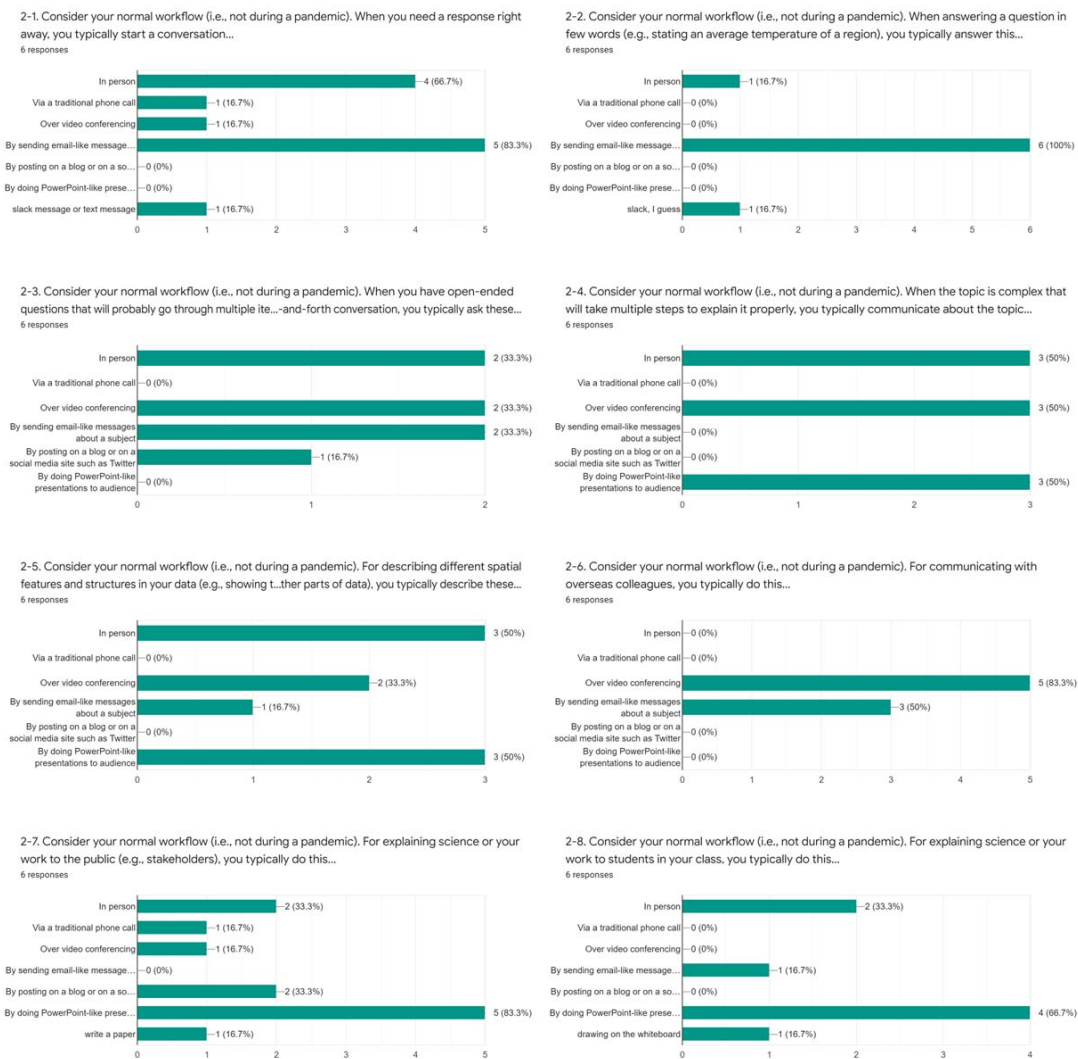
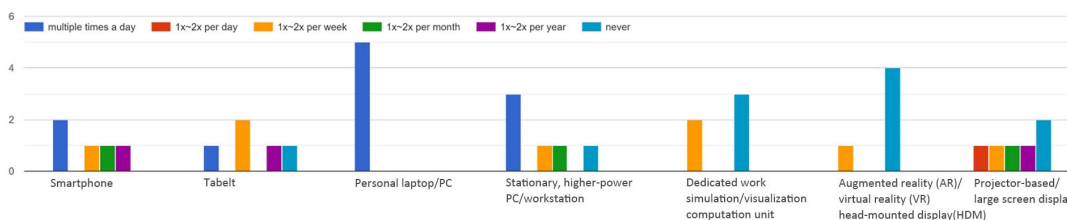


Figure 5.10: Participant responses from the pre-study questionnaire.

4-1. How many hours of your day do you have easy access to these devices? You have easy access to a device if you would be able to use it if you wanted to. Pick the hours next to each device. For example, since I work at a desk job, I would pick "4~8 hours" for "Stationary, higher-power PC/workstation". Think of your normal workflow (i.e., not during a pandemic).



4-2. How many times of your day do you use these devices for science-related communication? You can choose one of the options next to each device. For example, since I work at a desk job and collaborate with scientists from various domains, I would chose "multiple times a day" for "Work PC". Think of your normal workflow (i.e., not during a pandemic).

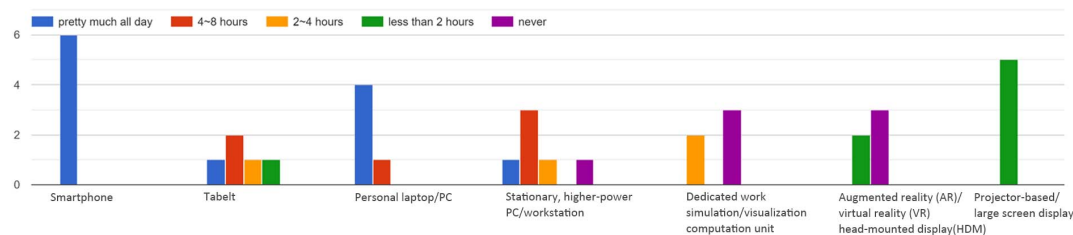


Figure 5.11: Participant responses from the pre-study questionnaire.

With regards to device-usages (Figure 5.11), participants typically have some access (2-8 hours) to high-end or specialized devices. However, they typically use personal PC/mobile devices for science-related communications. Two participants indicated that their responses to questions may vary depending on goals. A participant wrote that her usages of the devices change if she is working on a video or visualization project. A participant from the brain science team also wrote that, in clinics, radiologists use specialized monitors for viewing lossless DICOM images to see subtle differences in tissue contrasts.

### Produced V-Mails

Over the course of their work, the artist and science writer used V-Mail to brainstorm and storyboard multiple video sequences highlighting the science. The V-Mail exchanges center on fly-through animations of the visualization, and each data view is augmented with textual comments including a possible voice-over script. We show the resulting V-Mail, perhaps better thought of as a V-Mail

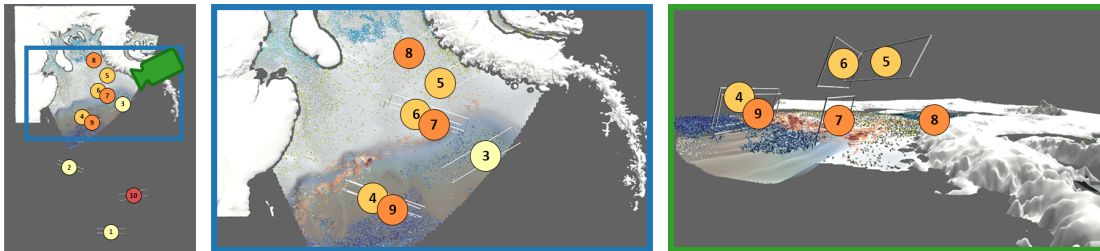


Figure 5.12: Visualizations of data views’ placements in the V-Mail participants created. Each circle represents a data view with a number indicating the view’s order and with color indicating its thematic section.

“thread,” as part of the supplementary material of this dissertation.

In total, the V-Mail contains ten data views (Figure 5.12). The first three (#1–#3) provide an overview of data visualization, highlighting all visible variables. The last shot (#10) is another overview shot. Data views in the middle (#4–#9) describe two different concepts about interactions of water masses and currents on the ice shelf. Each concept was communicated with three shots. The first (#4, #7) gives a spatial context, the second (#5, #8) zooms in further to focus on visual decisions, and the last (#6, #9) zooms in further to relate the visual decisions to specific data features. Each shot is discussed in detail with textual comments contributed by both artists.

The artist requested another version of the V-Mail that shows the fly-through animation at a higher resolution (1920x1080) and without the floating 3D pages. Treating it like a final draft of their work, the “final” V-Mail shows only the voice-over script, without all the low-level communications such as questions in a form of comments.

### Software logs

Our log data and users’ comments made in the story indicate that there were five back-and-forth communications over the two weeks (Table 5.2). In the first V-Mail, the artist captured data views with scripting guidelines written as comments. The science writer opened the V-Mail from the artist, then proceeded to work on

Table 5.2: Five back-and-forth communications between participants

#	User	Client	Goals	# of data views	# of edited data views	# of views with new comments	# of views with new sketches
1	artist	desktop	capture data views with scripting guidelines	15	15 added	13	0
2	writer	mobile	draft a voice-over script, ask questions	15	-	9	0
3	artist	desktop	answer questions, make requests	15	-	3	0
4	writer	mobile	make requests	15	-	5	0
5	author	desktop	address the requests	10	5 removed, 1 rearranged	0	0

drafting a voice-over script for each data view using the guidelines contained in the V-Mail. Additional comments were made in next two communications; most involved providing answers and making requests. In the final communication, a few data views were removed and a data view was rearranged in the sequence. At each turn, after making edits, the participants used their normal e-mail to pass the V-Mail link to each other and request comments. Both URL and name were used to reference updated V-Mails.

The textual comments were added to data views and were used mainly to provide guidelines and script a voice-over. Questions were also asked in a form of comments. For example, confused with the scripting guidelines, the science writer left questions on corresponding data views. We also found that the comments contained imperfections, like typos and this accidental use of caps lock, “hERE WE CAN SPEAK about.” Capitalization was also used for emphasis, as in “IGNORE the above.” The artist and science writer did not use the sketching feature to annotate data views.

The visual artist used the desktop client and the science writer used the mobile client. While working on the script, the science writer realized that a few data views were not needed. While working on the mobile client, she left comments on these extra data views to request a removal. Because the artist using the desktop client forgot how to remove data views and we (the authors) were also monitoring the communication, we were able to quickly help out and resolve the request in the desktop client.

### **Observations during introductory sessions**

At the end of each training session, we asked users to now begin to use the tool while we observed their actions and answered any questions that came up. We recorded several observations during this time,

In the first V-Mail, **the artist** captured data views with scripting guidelines written as comments (Table 5.2). The installation steps and training time for this took about 20 minutes for the desktop-client. She created three V-Mail drafts in the next hour session. She discarded two of them, and proceeded to refine to third

by adding a few more data views, rearranging their placement, and adding notes and guidelines to send to her colleague.

The artist created V-Mails with multiple sections (i. e., data views) to cover different data features (Figure 5.12) and used **different approaches** to extend and strengthen a story line as they worked. We noticed that the most recently added data view was often used as a spatial reference frame for the next data view. For example, after adding view #6, view #7 was described using the language, “now looking down and reveal the currents.” The participant also added data views “out of sequence” and rearranged previously added views to strengthen the story. For example, seeing the existing views #5 and #6, one participant decided to add a view showing all the discussed water masses. To specify this view, however, the participant first navigated to view #2, where the camera was positioned, to provide an overview that made it easy to zoom in to water masses of interest. Then, after adding a data view from the newly zoomed-in camera viewpoint, they rearranged the data views on the timeline to created the sequence #4–#6.

We also observed the artist **struggling** to perform certain tasks. While moving the camera, the artist mistakenly clicked a 3D floating frame, which moves the camera to a view location shown in the clicked frame. And this happened more frequently as more data views were added to the V-Mail. Also, she had to take multiple steps to move a data view placed at the end to the beginning as the current storyboard only shows five thumbnails at once and its scrolling feature does not work when the user is moving a thumbnail.

In the second V-Mail, **the science writer** opened the V-Mail from the artist, then proceeded to work on drafting a voice-over script for each data view using the guidelines contained in the V-Mail (Table 5.2). The science writer used the mobile-client as the features required for her tasks were available there. The installation steps and training time for this took about 5 minutes. She flipped through pre-existing data views and wrote the script as comments. She finished the task in next 30 minutes. No major difficulties while using the tool were reported by her.

## Feedback from User Interviews

After the participants creating their first V-Mails, we conducted interviews to learn more about how users' reacted to the tool.

The artist described gaps in their current tools and **relevant cases where V-Mail could be most useful**. The artist described her typical approach of creating a fly-through animation as, first, establishing the concepts to convey and, second, capturing the shots needed for the concepts. The process was described as “melding story into visuals.” For all but simple topics, in-person communication or video conferencing are preferred for describing such visual and spatial concepts, but in practice, they often resort to sending several fly-through animations to the scientists to confirm the concepts. In their traditional workflow, this process takes a long time as they often require technical assistance from additional team members to create their animations. The V-Mail approach, in contrast, enables artists, science writers, or other team members to control this process on their own. They can focus on identifying the right views to convey the concepts, and the animation is automatically created. The ability to quickly mock-up animations from data views expedites the creation process, and the ability to view the results on mobile devices and web browsers simplifies the distribution process.

Imagining how their experiences might translate to **a future trial with the larger group**, the artist pointed out that the mobile client will provide a means for the scientists to provide feedback without the need to go through complex installation steps and a long training. She also pointed out the importance of the web-client as it enables them to reach people outside of the group, e. g., the public and scientists from other groups.

The artist did not use **the sketching feature to annotate data views**, even though, in several data views, she described features at specific locations of the views (e. g., eddies formed in a current shown in the bottom). When asked about it during the interview, the artist explained that she thought this would be useful in some situations, but in this case she knew the science writer was already familiar with data features and visual mappings from their close recent work together.



Imagining how V-Mail could be integrated into current workflows, the science writer told us that V-Mail could be a group note-taking tool during **synchronized collaboration sessions**. For instance, as a member presents a V-Mail in a live video-conference session, other group members can take notes directly on the shared visualization results using their own clients. After the meeting, the members can share the annotated V-Mail to the group as a way to provide a visual summary of the discussion. Also, as pointed out by the science writer, these comments capture a history of the group decisions and work style that could be useful in summarizing discussions and introducing a project to new team members.

The participants made several **feature requests**. Interested in sharing their work to collaborating scientists and possibly using it as video footage for their next video projects, the artist requested a feature to save our the animation into a video file at a higher resolution (1920x1080) and without showing the floating 3D pages. We met this request in a later iteration. She also requested to implement additional V-Mail clients for ParaView [3], a visualization tool the team frequently uses. The science writer suggested supporting audio recording to annotate existing data views as it's often easier than writing thoughts down. The writer told us that opening a V-Mail takes a long-time. She suggested another data presentation mode that shows a V-Mail without the animated transitions, as this can reduce the download time and the animated transitions might not be needed for some users who are already familiar with data presented in the shared views. Also, in our current implementation, the user first needs to add a data view before annotating it. She suggested another approach where a data view is automatically added when the user starts drawing on the current camera view.

### **Feedback from scientists**

After the two weeks, the artist shared the resulting V-Mail in a regularly scheduled, “live” video-conference with the larger group, and led a discussion about the work using the web-client. The scientists were *surprised* because, with their traditional tools, it is difficult for them to create the path through the data in

such a controlled fashion. The scientists were most interested in seeing details of water-mass distributions, current trails, and their impacts to melting glaciers. The resulting V-Mail narrative covers these regions of interests and employs proper storytelling techniques—e. g., a series of first overview, then zoomed-in data views [98] connected with transitioning animations—to show not only details of these regions but also their contextual information. They were also interested in seeing changes of specific regions over time. Unfortunately, time-series data is not yet supported in the underlying visualization software. The scientists requested this as a future work and brainstormed ideas for storytelling techniques to convey these in future iterations. They envisioned to station the camera to focus on a specific region and then show changes over time. They would do this for multiple data regions and employ V-Mail’s interactive storytelling techniques to return to previous camera locations to facilitate comparative analysis of the sites.

### **Post-study Questionnaire**

One user from the climate science team participated in the questionnaire (A.3.2). In an open-ended comment section, the participant indicated that she plans to use the tool in the future. The ability to define view points and transition between these are useful as they are making movies or telling data stories. The ability to annotate on captured data views received a positive feedback. The textual comments helps her “craft the narrative”. The drawing features will enable the scientists to point out the specific features more quickly and accurately. The participant says connecting views with animations is a crucial component in data communication. However, the ability to pause in-between and play backwards received a neutral response. Also the ability to see the 3D frames received a neutral response.

The ability to distribute V-Mails to lightweight clients received a positive response. However, she showed concern about seeing her visualization on a small display as it is visually detailed. She gave a positive response to the web-client as this allows her to easily share the results with her collaborating scientists. The use of URL as a distribution mechanism also received a positive response. As a

future work, she requested a feature to output a video file without the frames and at a higher resolution.

### 5.5.3 Discussion and Interpretation

There are several themes emerged from our observations. Re-ordering existing data views happened throughout different phases of their collaboration and this has been a frequent discussion topic. For example, the artist added data views “out of sequence” and rearranged previously added views to strengthen the story while creating a V-Mail (Sessions). View rearrangements like these were also discussed in the textual comments (Software logs). The idea of new data views and their arrangements was also discussed in the live videoconference with the scientists (Feedback from scientists). The ability to extend existing V-Mails using different clients helped them iteratively create a data presentation as well as asynchronously discuss about data.

Annotations were used for more than scripting a voice-over. Confused with the scripting guidelines, the science writer left questions on corresponding data views. Several of these low-level communications were removed from the “final” V-Mail, which was used like a final draft of their work. However, both participants described the importance of “temporary” comments in this style for a group working towards a final product; they stated that these help them to clarify tasks and enable other team members to provide immediate help. We found that the comments contained imperfections, like typos and this accidental use of caps lock (Software logs). All of these reinforce the chat-like immediacy and draft-in-progress qualities of V-Mail. These qualities are unusual in science communication, especially high-end data visualization, but we believe they may, in fact, help to put a human face on science communication, helping scientists and stakeholders more freely discuss scientific data.

Participants tend to pick lightweight clients if features required for their tasks are available in those clients. The science writer used the mobile client when writing scripts to attach as comments to preexisting data views. Additionally, when sharing V-Mails in the live video-conference with the scientists, the artist

found the web client to be most convenient. Also described by the artist, these lightweight V-Mail clients would provide accessible means for a larger group of people to partake in collaborative storytelling in a future trial.

The brain science team described in the beginning of Section 5.5 meets regularly, almost weekly, over a live video conference or in a meeting room. The team uses remote asynchronous communication tools, such as emails, to coordinate these meetings or share dataset. This preference towards synchronized communication was also the case for the climate science team; the team prefers in-person or live video conferences over sending emails (Pre-study questionnaire). However, as multiple groups in different schedules are working together, the ability to communicate asynchronously is a necessity for the team. Thus, V-Mail became useful for them as it provides them the ability to create animated data stories and to discuss about findings asynchronously. Even though V-Mail could be used in a synchronous collaboration scenario (Interviews), email-like visual messaging tools might not be needed for teams who already have routines to share their work in regular meetings. This realization can help us deciding which team to show our tool in a future trial.

### **Limitations and Open Problems**

We also captured several suggestions for refinements, which highlight both limitations and directions for future work.

**Extending questionnaires and logging procedures:** In the pre-study questionnaire, participants indicated that their responses to questions may vary depending on goals. In the post-study questionnaire, participants would have made similar comments if their team had used our tool for different purposes which might be the case if they had used it for a longer trial period. Thus, we plan to update the questions to be more specific on given situations or provide the ability to describe a context before responding. The approach would be providing means to duplicate questions, if needed, and provide responses in different contexts. After gathering feedback, we code each response based on categories—public-facing presentation,

inner-group collaboration, or communication with external collaborators—to access usages of features/devices in relation to different goals in science-related communication. Additionally, we plan to update our logging procedure to be able to categorize the log data based on the communication goals. This can be done by letting users specify goals of creating data stories. For instance, when creating a data story for a broad audience, the user sets the story with tags, e.g., “public-facing” and “data video”. Having these tags associated with each story, we can categorize edits made in each story based on goals. With this procedure, we can then cross-check edits and responses to the questionnaires.

**Facilitating interactive storytelling on web-clients:** Over a video conference session, the brain science team suggested an interesting future direction where our tool provides supplementary materials for research papers. They envision another web-client that support accessible, interactive storytelling techniques, being almost like our mobile-client, this client will enable reviewers and readers to validate claims made in the papers and explore data views shown in figures. In addition to the 360-degree viewer in our mobile-client, we plan to integrate additional intelligent viewers for interactive storytelling that build upon existing techniques such as hover-over interactions [43] and filtering tasks [107].

**Evaluating in other collaboration scenarios:** As V-Mail was not integrated into their regular visualization tools, the brain science team decided not to be part of a multi-week trial. We decided to address this in the future as it would require major updates to our implementation (their software are built-in C++ whereas ours in C#-based Unity3D). If were to evaluate V-Mail in other situations and domains, we first need to address this issue. Our next step should be decoupling the storytelling part of V-Mail from underlying exploratory visualization software, as it will help us integrating software built-in other languages and ease the integration process. Additionally, V-Mail was evaluated in scenarios where only a smaller number of experts from a science group were involved in collaboration. We plan to evaluate our concept and implementation in situations

where more people from diverse backgrounds are part of collaboration, e.g., scientists teaching a classroom or a group creating video-based visualizations for their department as this would encourage participants from non-experts such as people working at front-office and marketing.

**Adjustment to additional visualization software:** The major current limitation is a need for additional clients to use V-Mail with additional visualization tools, such as ParaView [3]. As useful visualization tools are written in many different languages, we are considering decoupling the storytelling parts of V-Mail from exploratory parts that are heavily integrated into underlying software which could be done by creating a separate storyboard application that communicates over the network with other visualization software. The storyboard application would be similar to our mobile client in that it shows clips captured from data visualization software but enables editing stories and supports exploration by updating connected software. This V-Mail would require some client-specific code, specifically the routines to save out visualization states and compare these states are specific to each new software, but the integration effort would be minimized and any open-source visualization software could be supported. Since the webpage and the mobile app do not rely on other data visualization applications (these clients play a video), we can continue using these clients for showing and interacting with stories created from new connected software.

**De-emphasizing storytelling components:** The artist requested a feature to hide visual components such as drawings and floating frames as she wanted to use the camera animation to create a longer documentary-style video (Interviews). This request, however, helped us to realize a current limitation: even though V-Mail is built on top of an exploratory visualization framework, its visuals are always present. They can thus block the view of a user who is done with a story and now focuses on data analysis or other related tasks. This issue could be addressed by providing a toggle button to hide/show the visual components. Another possibility would be to automatically resize the 3D frames depending on

their distance from the camera. As the camera gets closer to a given data view, its corresponding frame could get smaller to reduce its occlusion but to still provide its spatial context. Frames of distant data views would be rendered with larger dimensions to ensure their continued visibility.

**Supporting Juxtaposition Views and Data-Aware Annotations:** During presentation and discussion with colleagues, it is often useful to show multiple data views simultaneously, for instance, to support juxtaposition (side-by-side) comparisons [60, 35] or to provide a visual summary, which can be an important component in a data story [63]. In order to support this presentation style, we plan add a feature to our current Storyboard for creating a page composed of multiple data views and using this page as a keyframe in an animation. As hovering over a thumbnail on the Storyboard highlights the corresponding 3D view frame in our current implementation, hovering over this new page will zoom out the camera to show all the data views in the page and bring the camera back to its original location when the mouse moves off the page. Also we plan to integrate other means for the user to annotate the data, e. g., annotating with shapes and icons as done in [42] and for highlighting a portion of data to direct audience attention to a particular region using context-aware selection techniques such as [124].

## 5.6 Conclusion

On a conceptual level, our work extends the state of art on storytelling in visualization and provides a rich tool set for asynchronous remote collaboration. We build upon existing spatial 3D data storytelling techniques [5, 78] that tightly couple storytelling with data exploration and employ semi-automatic procedures to expedite the story creation process. What is unique in V-Mail is the ability to collectively work on data stories, which is often seen with abstract data visualization, e.g. via web-based visualizations [114, 42], but less so with visualization

of spatial 3D data. Essentially this multi-author edits in V-Mail is a type of parallel storytelling [108] with the difference that users not only view or edit shared data stories but also do this across different devices. V-Mail is thus an example of using multiple display devices in collaborative data visualization [52, 53]. However, V-Mail focuses on asynchronous remote communication and provides lightweight mobile and web clients for partaking in collaboration and simplifies the distribution process using URLs to reference data stories.

The desktop-client is an example of asynchronous collaboration frameworks that support collaborative activities around exploratory visualizations, e.g., as done in [42, 5, 27, 119]. The mobile-client, however, supports these activities around video-based visualizations created from the desktop-client. The ability to provide visual feedback directly onto shared visualization results is similar to the ability to annotate on shared data views and stories in the web-based visualization [42]. However, there are two major differences in our approach: 1) communication mechanisms are tailored for spatial 3D data visualization, e.g. with spatial annotations and animated transitions, and 2) the app is designed to solely work with shared visualization results. The latter point may be of interest to visualization practitioners as this approach enables them to bypass installation steps and computation requirements often imposed by using exploratory visualization software such as ParaView [3]. Also this separation suggests an interesting future direction of turning V-Mail into a collaborative framework that unifies well-known software in the field for creating data stories and conducting discussion.



## Chapter 6

# Conclusion

We revisit the central thesis and present a discussion of future work.

### 6.1 Revisiting Our Central Thesis

The central thesis behind Everyday Scientific Visualization is:

*Making communication the number one design goal for spatial 3D visualization leads to new engaging, accessible, and collaborative tools that can shift scientific visualization from a rare, special activity to an everyday tool for data analysis and communication.*

In Chapter 3, we introduced a visualization for exploring the FIA dataset [88], an example of high-end scientific datasets. Compared to existing approaches of sharing the data in spreadsheets on a government’s website, our approach constructs data-driven virtual worlds and integrates immersive display technologies so that the public has more engaging, accessible options to look at the data. Additionally, the visualization technique enables users to simultaneously view multiple data-driven environments, which allows them to do comparison-based exploration and presentation. This work, thus, supports our claim by providing scientists with an engaging approach for the public to explore the scientific data, which could well

be used for showcasing scientific work in classrooms or to visitors at a research facility. However, this work partially supports the claim, as accessibility to the technology is limited.

In Chapter 4, we addressed this issue and presented a lightweight visualization that supports exploration of the same dataset used in our previous technique. Our approach provides an immersive view of the data-driven environments on a mobile device and integrates 2D map visualization and interaction techniques already familiar to general audience. This approach has a limited flexibility compared to the one in Chapter 3, but this enables scientists to share their work at a larger scale and in various contexts. However, this and our previous technique do not facilitate collaboration across these different devices and with users in different spaces/times.

Therefore, in Chapter 5, we focused on providing accessibility to communication. We presented a collaborative visualization framework that enable 3D-enabled correspondences about data across different devices. The flexible message protocol, with support for bi-directional communication, allows multiple users to conduct collaborative discussion. The lightweight clients facilitate more frequent discussion about spatial 3D data analysis. Finally, by integrating storytelling metaphors with support for annotations and animations, visualization results are described in steps and in more understandable forms. With the storytelling, multi-author edits, and different device clients, our approach supports collaborative discussion of spatial data analysis in dynamic settings, thereby supporting the rest of our thesis, which is facilitating engaging, accessible, everyday communication.

In summary, the basis of Everyday Scientific Visualization techniques is an improved human-to-human communication about data that broadens the scope of possible users and use-cases. These provide *engaging approaches* for non-experts to explore high-end scientific data by enabling scientists to employ storytelling, immersive display technologies for presenting their scientific data. These also provide *accessible options* for exploring scientific data and partaking in data collaboration with lightweight clients that support visualization tasks on accessible

mobile devices. Finally, different visualization clients with flexible message protocols enable team members to *collaborate in various situations*, without constraints of space and time as well as with a flexibility of choosing devices and contexts to partake in collaboration. And these visualization tools have shown to be effective and useful in context of data exploration, education, and team-science collaboration, indicating us that scientific visualizations can indeed be *everybody’s tools and everyday tools for data analysis and communication*.

## 6.2 Future Work

We describe directions for future work.

### 6.2.1 Additional Devices and Media Formats

The current V-Mail clients support some mobile devices (Android, not yet iOS) and web-browsers that provide lightweight means of partaking in collaboration. In this dissertation, we also showed two examples of Immersive Data Visualization that provide two complementary approaches of presenting spatial 3D dataset. We are thus interested in supporting these approaches with additional V-Mail clients that will enable audiences to use AR or VR headsets to explore shared data and stories in the style of Boom Chameleon [110], with the ability to leave notes and draw directly on a 3D space (e.g., [57, 49]). Interested in seeing findings on a topic, one can place related data stories into multiple wedges (see Chapter 3) to find similarities or differences. The mobile app in Chapter 4 can provide a lightweight VR client with support for multi-touch interactions.

We also are interested in developing V-Mail clients to support additional hardware and media. With the help of wearable technologies such as smartwatches, audiences could also quickly see updates from others and provide simple feedback, e.g., by pressing on a data view to give a thumbs-up approval. Building upon the creative use of postcards in “Dear Data” [79], V-Mail stories could also be printed on physical postcards; audiences would receive stories in their mailbox with a series of data views printed in the front and room for comments on the

back. Writing and drawing on the postcard could be captured and shared to the original sender, which could be done by taking a photo of the postcard, separating the notes from the printed views, and adding these notes back to the original data.

### 6.2.2 An Unifying Storytelling Platform

Teams to whom we showed the tool typically use more than one data visualization software. The storyboard application we discussed in Section 5.5.3 creates the possibility of telling data stories and conducting collaborative analysis across multiple data visualization software in an unifying platform. For instance, connected to ParaView [3] and the ABR framework [55], this new storyboard application will use clips from both software and create data stories highlighting differences in visualization techniques. Also clicking a data view captured from ParaView will not only update ParaView but also update the connected ABR framework, facilitating data comparisons in these linked data visualizations. As the teams also employ non-spatial data visualizations in their data analysis and communication, we should also consider the possibility of connecting non-spatial or 2D data visualization software, e.g., Tableau and Excel. This also raises interesting future research questions such as how to deal with animated transitions between different visualization types and showing annotations from a visualization in another, which have been studied by Heer and Robertson [41] and Kim et al. [59], but not to the extent in which the transformations occur between spatial to non-spatial data visualizations.

### 6.2.3 Casting Scientific Visualization as Social Spaces

Heer et al. describe mechanisms that cast visualizations as social spaces [42] where online users can stumble into or look for discussions and presentations around data visualizations. We are inspired by these. For instance, by supporting a log-in and tracking users' activities, we can provide a profile page where online users can look for stories and comments left by the profile user. Also by taking advantage of spatial information stored in a V-Mail story, we can support a search

mechanism based on locations of data views in a story. For instance, to see on-going discussions, a scientist can pick a particular region in data to search for stories that contain data views near the region. With these search (social navigation [42]) mechanisms along with the ability to use a diverse set of devices, spatial data visualization often discussed in a lab by a few expert users could be shared and, most importantly, discussed with fellow citizens.

### 6.3 General Conclusions

This dissertation aims to make scientific visualizations accessible for day-to-day operation of team-science. There are common themes in our approach that can provide guidelines for designing visualization and interaction methods.

Our techniques are built on top of existing visualization approaches which allows users to easily switch between performing typical analysis tasks and additional ones. Worlds-in-Wedges described in Chapter 3 enables both typical VR-based exploration of 3D spatial data as well as comparisons of multiple virtual worlds. The desktop-client from Chapter 5 is capable of supporting tasks on a wide spectrum of author-driven and reader-driven storytelling [40], enabling audience to explore presented dataset at any point in a data story, e.g. to test claims made in presentations.

The work presented in this dissertation are examples of exploration visualization [123] with emphasis on providing accessibility to a large audience. The lightweight apps described in Chapter 4 and 5 provide less features compared to desktop-based applications in Chapter 3 and 5. However, these apps provide accessible options for supporting exploration and collaborative discussion of spatial 3D dataset. Importantly, annotations made in these lightweight visualization clients are made back to the original data, enabling users of high-end systems or other devices see the changes. The designs and implementations may be of interest to visualization practitioners looking for ways to showcase their high-end spatial 3D visualizations and to facilitate collaborative discussion of 3D data analysis.

We focus on providing accessibility to communication of spatial 3D data visualizations. This approach differs from remote rendering techniques, e.g., [77], that focuses on providing accessibility to full-exploratory capabilities of high-end visualizations. We focus on techniques that facilitate communication of data such as supporting annotations, exports of visualization results, distributable file formats, etc. Building upon existing work that facilitate collaborative presentations but focuses on non-spatial visualization, e.g., web-based visualizations [42, 114], we introduce a collaborative framework tailored for spatial 3D datasets, e.g., with support for spatial annotations and animations. Due to computation requirements often imposed by scientific visualization software, e.g. ParaView [3], we also take the approach of facilitating collaborations around visualization results exported from high-end systems. Also this separation to underlying visualization software suggests an interesting future direction of turning V-Mail into a framework that unifies well-known software in the field for creating data stories and conducting collaborative discussion of various types of data.

# References

- [1] D. Acevedo, E. Vote, D. H. Laidlaw, and M. S. Jukowsky. Archaeological data visualization in VR: Analysis of lamp finds at the Great Temple of Petra, a case study. In *Proceedings Visualization, 2001. VIS'01.*, pages 493–597. IEEE, 2001.
- [2] A. C. Addison. Emerging trends in virtual heritage. *IEEE multimedia*, 7(2):22–25, 2000.
- [3] J. Ahrens, B. Geveci, and C. Law. Paraview: An end-user tool for large data visualization. *The visualization handbook*, 717(8), 2005.
- [4] J. Ahrens, S. Jourdain, P. OLeary, J. Patchett, D. H. Rogers, and M. Petersen. An image-based approach to extreme scale in situ visualization and analysis. In *SC'14: Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*, pages 424–434. IEEE, 2014.
- [5] H. Akiba, C. Wang, and K.-L. Ma. Anviz: A template-based animation tool for volume visualization. *IEEE Computer Graphics and Applications*, 30(5):61–71, 2010.
- [6] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 chi conference on human factors in computing systems*, pages 1968–1979. ACM, 2016.

- [7] B. Bach, N. Kerracher, K. W. Hall, S. Carpendale, J. Kennedy, and N. Henry Riche. Telling stories about dynamic networks with graph comics. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 3670–3682, 2016.
- [8] B. Bach, Z. Wang, M. Farinella, D. Murray-Rust, and N. Henry Riche. Design patterns for data comics. In *Proceedings of the 2018 chi conference on human factors in computing systems*, pages 1–12, 2018.
- [9] L. Besançon, A. Ynnerman, D. F. Keefe, L. Yu, and T. Isenberg. The state of the art of spatial interfaces for 3d visualization. In *Computer Graphics Forum*, volume 40, pages 293–326. Wiley Online Library, 2021.
- [10] K. Bladin, E. Axelsson, E. Broberg, C. Emmart, P. Ljung, A. Bock, and A. Ynnerman. Globe browsing: Contextualized spatio-temporal planetary surface visualization. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):802–811, 2017.
- [11] T. Blascheck, L. Besançon, A. Bezerianos, B. Lee, and P. Isenberg. Glanceable visualization: Studies of data comparison performance on smart-watches. *IEEE transactions on visualization and computer graphics*, 25(1):630–640, 2019.
- [12] M. Bolas, J. Iliff, P. Hoberman, N. Burba, T. Phan, I. McDowall, P. Luckey, and D. M. Krum. Open Virtual Reality. In *2013 IEEE Virtual Reality (VR)*, pages 183–184. IEEE, 2013.
- [13] G. Bruder, F. Steinicke, and K. H. Hinrichs. Arch-explore: A natural user interface for immersive architectural walkthroughs. In *2009 IEEE Symposium on 3D User Interfaces*, pages 75–82. IEEE, 2009.
- [14] C. Bryan, K.-L. Ma, and J. Woodring. Temporal summary images: An approach to narrative visualization via interactive annotation generation and placement. *IEEE transactions on visualization and computer graphics*, 23(1):511–520, 2016.



- [15] W. Büschel, J. Chen, R. Dachselt, S. Drucker, T. Dwyer, C. Görg, T. Isenberg, A. Kerren, C. North, and W. Stuerzlinger. Interaction for immersive analytics. In *Immersive analytics*, pages 95–138. Springer, 2018.
- [16] D. Coffey, N. Malbraaten, T. B. Le, I. Borazjani, F. Sotiropoulos, A. G. Erdman, and D. F. Keefe. Interactive slice WIM: Navigating and interrogating volume data sets using a multisurface, multitouch VR interface. *IEEE Transactions on Visualization and Computer Graphics*, 18(10):1614–1626, 2011.
- [17] D. Coffey, F. Korsakov, M. Ewert, H. Hagh-Shenas, L. Thorson, A. Ellingson, D. Nuckley, and D. F. Keefe. Visualizing motion data in virtual reality: Understanding the roles of animation, interaction, and static presentation. In *Computer Graphics Forum*, volume 31, pages 1215–1224. Wiley Online Library, 2012.
- [18] D. Coffey, F. Korsakov, M. Ewert, H. Hagh-Shenas, L. Thorson, A. Ellingson, D. Nuckley, and D. F. Keefe. Visualizing motion data in virtual reality: Understanding the roles of animation, interaction, and static presentation. In *Computer Graphics Forum*, volume 31, pages 1215–1224. Wiley Online Library, 2012.
- [19] D. Coffey, N. Malbraaten, T. B. Le, I. Borazjani, F. Sotiropoulos, A. G. Erdman, and D. F. Keefe. Interactive slice wim: Navigating and interrogating volume data sets using a multisurface, multitouch vr interface. *IEEE Transactions on Visualization and Computer Graphics*, 18(10):1614–1626, 2012.
- [20] S. V. Collaborative. Salt, chemistry and cultivation: An immersive experience of climate data in the gulf of mexico. Accepted to South by Southwest (SXSW) Festival 2020, Austin, TX (Delayed due to Pandemic), March 2020.
- [21] M. Cordeil, A. Cunningham, T. Dwyer, B. H. Thomas, and K. Marriott. Imaxes: Immersive axes as embodied affordances for interactive multivariate

- data visualisation. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, pages 71–83, 2017.
- [22] M. Cordeil, A. Cunningham, B. Bach, C. Hurter, B. H. Thomas, K. Marriott, and T. Dwyer. IATK: An immersive analytics toolkit. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 200–209. IEEE, 2019.
- [23] P. de Lange, P. Nicolaescu, J. Benschaid, and R. Klamma. Collaborative non-linear storytelling around 3d objects. In *International Conference on Web-Based Learning*, pages 88–98. Springer, 2018.
- [24] C. Demiralp, C. D. Jackson, D. B. Karelitz, S. Zhang, and D. H. Laidlaw. Cave and fishtank virtual-reality displays: A qualitative and quantitative comparison. *IEEE transactions on visualization and computer graphics*, 12(3):323–330, 2006.
- [25] K. Devlin, A. Chalmers, D. Brown, et al. Predictive lighting and perception in archaeological representations. In *Conference proceedings of UNESCO World Heritage in the Digital Age: 30th Anniversary Digital Congress (October, 2002)*, [URL: [http://doc. gold. ac. uk/~mas01dl/CIS224b/unesco-paper. pdf](http://doc.gold.ac.uk/~mas01dl/CIS224b/unesco-paper.pdf)]. *Acceso*, volume 14, page 2014, 2002.
- [26] N. Duarte. *Data story: Explain data and inspire action through story*. Idea-press Publishing, 2019.
- [27] R. Eccles, T. Kapler, R. Harper, and W. Wright. Stories in geotime. *Information Visualization*, 7(1):3–17, 2008.
- [28] H. Farooq, J. Xu, J. W. Nam, D. F. Keefe, E. Yacoub, T. Georgiou, and C. Lenglet. Microstructure imaging of crossing (mix) white matter fibers from diffusion mri. *Scientific reports*, 6:38927, 2016.
- [29] A. Fonnet and Y. Prie. Survey of immersive analytics. *IEEE transactions on visualization and computer graphics*, 2019.

- [30] A. Forsberg, K. Herndon, and R. Zeleznik. Aperture based selection for immersive virtual environments. In *Proceedings of the 9th annual ACM symposium on User interface software and technology*, pages 95–96, 1996.
- [31] A. Forsberg, G. Haley, A. Bragdon, J. Levy, C. I. Fassett, D. Shean, J. Head, S. Milkovich, M. A. Duchaineau, et al. Adviser: immersive field work for planetary geoscientists. *IEEE computer graphics and applications*, 26(4): 46–54, 2006.
- [32] A. S. Forsberg, D. H. Laidlaw, A. Van Dam, R. M. Kirby, G. E. Kafniadakis, and J. L. Elion. Immersive virtual reality for visualizing flow through an artery. In *Proceedings Visualization 2000. VIS 2000 (Cat. No. 00CH37145)*, pages 457–460. IEEE, 2000.
- [33] C.-W. Fu, W.-B. Goh, and J. A. Ng. Multi-touch techniques for exploring large-scale 3D astrophysical simulations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2213–2222, 2010.
- [34] N. Gershon and W. Page. What storytelling can do for information visualization. *Communications of the ACM*, 44(8):31–37, 2001.
- [35] M. Gleicher. Considerations for visualizing comparison. *IEEE transactions on visualization and computer graphics*, 24(1):413–423, 2017.
- [36] M. Gleicher, D. Albers, R. Walker, I. Jusufi, C. D. Hansen, and J. C. Roberts. Visual comparison for information visualization. *Information Visualization*, 10(4):289–309, 2011.
- [37] Google. Google Cardboard. <https://vr.google.com/cardboard/>, 2014.
- [38] H. Haase, J. Strassner, and F. Dai. VR techniques for the investigation of molecule data. *Computers & Graphics*, 20(2):207–217, 1996.
- [39] M. S. Hancock, F. D. Vernier, D. Wigdor, S. Carpendale, and C. Shen. Rotation and translation mechanisms for tabletop interaction. In *Horizontal*

- Interactive Human-Computer Systems, 2006. TableTop 2006. First IEEE International Workshop on*, pages 8–pp. IEEE, 2006.
- [40] J. Heer and M. Agrawala. Design considerations for collaborative visual analytics. *Information visualization*, 7(1):49–62, 2008.
- [41] J. Heer and G. Robertson. Animated transitions in statistical data graphics. *IEEE transactions on visualization and computer graphics*, 13(6):1240–1247, 2007.
- [42] J. Heer, F. B. Viégas, and M. Wattenberg. Voyagers and voyeurs: supporting asynchronous collaborative information visualization. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1029–1038. ACM, 2007.
- [43] J. Heer, F. Van Ham, S. Carpendale, C. Weaver, and P. Isenberg. Creation and collaboration: Engaging new audiences for information visualization. In *Information Visualization*, pages 92–133. Springer, 2008.
- [44] A. J. Hey, S. Tansley, K. M. Tolle, et al. *The fourth paradigm: data-intensive scientific discovery*, volume 1. Microsoft research Redmond, WA, 2009.
- [45] J. Hullman, S. Drucker, N. H. Riche, B. Lee, D. Fisher, and E. Adar. A deeper understanding of sequence in narrative visualization. *IEEE Transactions on visualization and computer graphics*, 19(12):2406–2415, 2013.
- [46] P. Isenberg, N. Elmqvist, J. Scholtz, D. Cernea, K.-L. Ma, and H. Hagen. Collaborative visualization: Definition, challenges, and research agenda. *Information Visualization*, 10(4):310–326, 2011.
- [47] T. Isenberg. Interactive exploration of three-dimensional scientific visualizations on large display surfaces. In *Collaboration Meets Interactive Spaces*, pages 97–123. Springer, 2016.
- [48] S. Iserhardt-Bauer, P. Hastreiter, T. Ertl, K. Eberhardt, and B. Tomandl. Case study: medical web service for the automatic 3d documentation for

- neuroradiological diagnosis. In *Proceedings Visualization, 2001. VIS'01.*, pages 425–581. IEEE, 2001.
- [49] B. Jackson and D. F. Keefe. Lift-off: Using reference imagery and freehand sketching to create 3d models in vr. *IEEE transactions on visualization and computer graphics*, 22(4):1442–1451, 2016.
- [50] B. Jackson, D. Coffey, and D. F. Keefe. Force Brushes: Progressive data-driven haptic selection and filtering for multi-variate flow visualizations. *Proceedings of EuroVis 2012*, pages 7–11, 2012.
- [51] Y. Jansen. *Physical and tangible information visualization*. PhD thesis, Université Paris Sud-Paris XI, 2014.
- [52] D. H. Jeong, E. Suma, T. Butkiewicz, W. Ribarsky, and R. Chang. A continuous analysis process between desktop and collaborative visual analytics environments. In *2010 IEEE Symposium on Visual Analytics Science and Technology*, pages 231–232. IEEE, 2010.
- [53] D. H. Jeong, S.-Y. Ji, E. A. Suma, B. Yu, and R. Chang. Designing a collaborative visual analytics system to support users’ continuous analytical processes. *Human-centric Computing and Information Sciences*, 5(1):5, 2015.
- [54] S. Johnson, D. Orban, H. B. Runesha, L. Meng, B. Juhnke, A. Erdman, F. Samsel, and D. F. Keefe. Bento box: An interactive and zoomable small multiples technique for visualizing 4d simulation ensembles in virtual reality. *Frontiers in Robotics and AI*, 6:61, 2019.
- [55] S. Johnson, F. Samsel, G. Abram, D. Olson, A. J. Solis, B. Herman, P. J. Wolfram, C. Lenglet, and D. F. Keefe. Artifact-based rendering: Harnessing natural and traditional visual media for more expressive and engaging 3D visualizations. *TVCG*, 26(1):492–502, 2019. doi:10.1109/TVCG.2019.2934260.

- [56] D. Jönsson, M. Falk, and A. Ynnerman. Intuitive exploration of volumetric data using dynamic galleries. *IEEE Transactions on Visualization and Computer graphics*, 22(1):896–905, 2015.
- [57] D. F. Keefe, D. A. Feliz, T. Moscovich, D. H. Laidlaw, and J. J. LaViola Jr. Cavepainting: A fully immersive 3d artistic medium and interactive experience. In *Proceedings of the 2001 symposium on Interactive 3D graphics*, pages 85–93, 2001.
- [58] K. Kim, B. Jackson, I. Karamouzas, M. Adeagbo, S. J. Guy, R. Graff, and D. F. Keefe. Bema: A multimodal interface for expert experiential analysis of political assemblies at the pnyx in ancient greece. In *Proceedings of the IEEE Symposium on 3D User Interfaces*, pages 19–26, 2015.
- [59] K. Kim, B. Jackson, I. Karamouzas, M. Adeagbo, S. J. Guy, R. Graff, and D. F. Keefe. Bema: A multimodal interface for expert experiential analysis of political assemblies at the Pnyx in ancient Greece. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 19–26. IEEE, 2015.
- [60] K. Kim, J. V. Carlis, and D. F. Keefe. Comparison techniques utilized in spatial 3d and 4d data visualizations: A survey and future directions. *Computers & Graphics*, 67:138–147, 2017.
- [61] T. Klein, L. Autin, B. Kozlíková, D. S. Goodsell, A. Olson, M. E. Gröller, and I. Viola. Instant construction and visualization of crowded biological environments. *IEEE transactions on visualization and computer graphics*, 24(1):862–872, 2017.
- [62] C. N. Knaffic. *Storytelling with data: A data visualization guide for business professionals*. John Wiley & Sons, 2015.
- [63] R. Kosara. An argument structure for data stories. In *Proceedings of the Eurographics/IEEE VGTC Conference on Visualization: Short Papers*, pages 31–35, 2017.

- [64] R. Kosara and J. Mackinlay. Storytelling: The next step for visualization. *Computer*, 46(5):44–50, 2013.
- [65] D. Kouřil, O. Strnad, P. Mindek, S. Halladjian, T. Isenberg, M. E. Gröller, and I. Viola. Molecumentary: Adaptable narrated documentaries using molecular visualization. *TVCG*, 2022. doi: 10.1109/TVCG.2021.3130670. To appear.
- [66] A. Kuhn and M. Stocker. Codetimeline: Storytelling with versioning data. In *2012 34th International Conference on Software Engineering (ICSE)*, pages 1333–1336. IEEE, 2012.
- [67] A. Kunert, A. Kulik, S. Beck, and B. Froehlich. Photoportals: shared references in space and time. In *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing*, pages 1388–1399, 2014.
- [68] J. J. LaViola Jr, D. A. Feliz, D. F. Keefe, and R. C. Zeleznik. Hands-free multi-scale navigation in virtual environments. In *Proceedings of the 2001 symposium on Interactive 3D graphics*, pages 9–15. ACM, 2001.
- [69] B. Lee, R. H. Kazi, and G. Smith. Sketchstory: Telling more engaging stories with data through freeform sketching. *IEEE transactions on visualization and computer graphics*, 19(12):2416–2425, 2013.
- [70] B. Lee, N. H. Riche, P. Isenberg, and S. Carpendale. More than telling a story: Transforming data into visually shared stories. *IEEE computer graphics and applications*, 35(5):84–90, 2015.
- [71] B. Lee, T. Dwyer, D. Baur, and X. G. Veira. Watches to augmented reality: Devices and gadgets for data-driven storytelling. In *Data-driven storytelling*, pages 135–149. AK Peters/CRC Press, 2018.
- [72] B. Lee, B. Bach, T. Dwyer, and K. Marriott. Immersive Analytics, aug 2019. ISSN 15581756.

- [73] J. Liang and M. Green. Jdcad: A highly interactive 3d modeling system. *Computers & graphics*, 18(4):499–506, 1994.
- [74] I. Liao, W.-H. Hsu, and K.-L. Ma. Storytelling via navigation: A novel approach to animation for scientific visualization. In *International Symposium on Smart Graphics*, pages 1–14. Springer, 2014.
- [75] E. M. Lidal, H. Hauser, and I. Viola. Geological storytelling: graphically exploring and communicating geological sketches. In *Proceedings of the International Symposium on Sketch-Based Interfaces and Modeling*, pages 11–20, 2012.
- [76] E. M. Lidal, M. Natali, D. Patel, H. Hauser, and I. Viola. Geological storytelling. *Computers & graphics*, 37(5):445–459, 2013.
- [77] E. J. Luke and C. D. Hansen. *Semotus visum: a flexible remote visualization framework*. IEEE, 2002.
- [78] P. Lundblad and M. Jern. Geovisual analytics and storytelling using html5. In *2013 17th International Conference on Information Visualisation*, pages 263–271. IEEE, 2013.
- [79] G. Lupi and S. Posavec. *Dear data*. Chronicle books, 2016.
- [80] K.-L. Ma and C. Wang. Social-aware collaborative visualization for large scientific projects. In *2008 International Symposium on Collaborative Technologies and Systems*, pages 190–195. IEEE, 2008.
- [81] K.-L. Ma, I. Liao, J. Frazier, H. Hauser, and H.-N. Kostis. Scientific storytelling using visualization. *IEEE Computer Graphics and Applications*, 32(1):12–19, 2011.
- [82] K.-L. Ma, I. Liao, J. Frazier, H. Hauser, and H.-N. Kostis. Scientific storytelling using visualization. *IEEE Computer Graphics and Applications*, 32(1):12–19, 2012.



- [83] M. Meuschke, L. Garrison, N. Smit, S. Bruckner, K. Lawonn, and B. Preim. Towards narrative medical visualization. *arXiv preprint arXiv:2108.05462*, 2021.
- [84] C. Mouton, K. Sons, and I. Grimstead. Collaborative visualization: current systems and future trends. In *Proceedings of the 16th international conference on 3D web technology*, pages 101–110, 2011.
- [85] T. Munzner. *Visualization analysis and design*. AK Peters/CRC Press, 2014.
- [86] J. W. Nam, K. McCullough, J. Tveite, M. M. Espinosa, C. H. Perry, B. T. Wilson, and D. F. Keefe. Worlds-in-Wedges: Combining WIMs and Portals to Support Comparative Immersive Visualization of Forestry Data. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2019.
- [87] C. North and B. Shneiderman. Snap-Together Visualization: A User Interface for Coordinating Visualizations via Relational Schemata. In *the Working Conference on Advanced Visual Interfaces (AVI)*, pages 128–135. ACM, 2000.
- [88] B. M. O’Connell, B. L. Conkling, A. M. Wilson, E. A. Burrill, J. A. Turner, S. A. Pugh, G. Christiansen, T. Ridley, and J. Menlove. *The Forest Inventory and Analysis Database: Database description and user guide version 7.0 for Phase 2*. U.S. Department of Agriculture, Forest Service. 830 p., 2017. URL <http://www.fia.fs.fed.us/library/database-documentation/>.
- [89] R. Olanda, M. Pérez, P. Morillo, M. Fernández, and S. Casas. Entertainment virtual reality system for simulation of spaceflights over the surface of the planet mars. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pages 123–132. ACM, 2006.
- [90] R. Pausch, T. Burnette, D. Brockway, and M. E. Weiblen. Navigation and

- locomotion in virtual worlds via flight into hand-held miniatures. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 399–400. ACM, 1995.
- [91] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected walking. In *Proceedings of EUROGRAPHICS*, volume 9, pages 105–106. Citeseer, 2001.
- [92] N. H. Riche, C. Hurter, N. Diakopoulos, and S. Carpendale. *Data-driven storytelling*. CRC Press, 2018.
- [93] O. . Samsung. Gear VR. <https://www.oculus.com/gear-vr/>, 2015.
- [94] P. Saraiya, C. North, and K. Duca. An insight-based methodology for evaluating bioinformatics visualizations. *IEEE transactions on visualization and computer graphics*, 11(4):443–456, 2005.
- [95] D. Schroeder, F. Korsakov, J. Jolton, F. J. Keefe, A. Haley, and D. F. Keefe. Creating widely accessible spatial interfaces: Mobile vr for managing persistent pain. *IEEE computer graphics and applications*, 33(3):82–88, 2013.
- [96] E. Segel and J. Heer. Narrative visualization: Telling stories with data. *IEEE transactions on visualization and computer graphics*, 16(6):1139–1148, 2010.
- [97] E. Shen, S. Li, X. Cai, L. Zeng, and W. Wang. Save: saliency-assisted volume exploration. *Journal of Visualization*, 18(2):369–379, 2015.
- [98] B. Shneiderman. The eyes have it: A task by data type taxonomy for information visualizations. In *Proc. VL*, pages 336–343, Los Alamitos, 1996. doi: 10.1109/VL.1996.545307.
- [99] A. Steed. Towards a general model for selection in virtual environments. In *3D User Interfaces (3DUI'06)*, pages 103–110. IEEE, 2006.
- [100] F. Steinicke, G. Bruder, K. Hinrichs, M. Lappe, B. Ries, and V. Interrante. Transitional environments enhance distance perception in immersive virtual reality systems. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*, pages 19–26, 2009.

- [101] R. Stoakley, M. J. Conway, and R. Pausch. Virtual reality on a whim: interactive worlds in miniature. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 265–272. ACM Press/Addison-Wesley Publishing Co., 1995.
- [102] C. D. Stolper, B. Lee, N. H. Riche, and J. Stasko. Emerging and recurring data-driven storytelling techniques: Analysis of a curated collection of recent stories. *Microsoft Research, Washington, USA*, 2016.
- [103] N. Sultanum, E. Sharlin, M. C. Sousa, D. N. Miranda-Filho, and R. Eastick. Touching the Depths: Introducing Tabletop Interaction to Reservoir Engineering. In *ACM International Conference on Interactive Tabletops and Surfaces, ITS '10*, pages 105–108, New York, NY, USA, 2010. Association for Computing Machinery. ISBN 9781450303996. doi: 10.1145/1936652.1936671. URL <https://doi.org/10.1145/1936652.1936671>.
- [104] N. Sultanum, S. Somanath, E. Sharlin, and M. C. Sousa. “Point It, Split It, Peel It, View It”: Techniques for Interactive Reservoir Visualization on Tabletops. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces, ITS '11*, pages 192–201, New York, NY, USA, 2011. Association for Computing Machinery. ISBN 9781450308717. doi: 10.1145/2076354.2076390. URL <https://doi.org/10.1145/2076354.2076390>.
- [105] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte. Leveraging change blindness for redirection in virtual environments. In *Virtual Reality Conference (VR), 2011 IEEE*, pages 159–166. IEEE, 2011.
- [106] M. Thöny, R. Schnürer, R. Sieber, L. Hurni, and R. Pajarola. Storytelling in interactive 3d geographic visualization systems. *ISPRS International Journal of Geo-Information*, 7(3):123, 2018.
- [107] A. Tikhonova, C. D. Correa, and K.-L. Ma. Explorable images for visualizing volume data. In *PacificVis*, pages 177–184. Citeseer, 2010.

- [108] C. Tong, R. Roberts, R. Borgo, S. Walton, R. Laramée, K. Wegba, A. Lu, Y. Wang, H. Qu, Q. Luo, et al. Storytelling and visualization: An extended survey. *Information*, 9(3):65, 2018.
- [109] R. Trueba, C. Andujar, and F. Argelaguet. Complexity and occlusion management for the world-in-miniature metaphor. In *International Symposium on Smart Graphics*, pages 155–166. Springer, 2009.
- [110] M. Tsang, G. W. Fitzmaurice, G. Kurtenbach, A. Khan, and B. Buxton. Boom chameleon: simultaneous capture of 3d viewpoint, voice and gesture annotations on a spatially-aware display. In *Proceedings of the 15th annual ACM symposium on User interface software and technology*, pages 111–120. ACM, 2002.
- [111] A. Van Dam, A. S. Forsberg, D. H. Laidlaw, J. J. LaViola, and R. M. Simpson. Immersive VR for scientific visualization: A progress report. *IEEE Computer Graphics and Applications*, 20(6):26–52, 2000.
- [112] A. Van Dam, D. H. Laidlaw, and R. M. Simpson. Experiments in immersive virtual reality for scientific visualization. *Computers & Graphics*, 26(4): 535–555, 2002.
- [113] J. Viega, M. J. Conway, G. Williams, and R. Pausch. 3D magic lenses. In *Proceedings of the 9th annual ACM symposium on User interface software and technology*, pages 51–58, 1996.
- [114] F. B. Viegas, M. Wattenberg, F. Van Ham, J. Kriss, and M. McKeon. Manyeyes: a site for visualization at internet scale. *IEEE transactions on visualization and computer graphics*, 13(6):1121–1128, 2007.
- [115] A. Wiebel, F. M. Vos, D. Foerster, and H.-C. Hege. Wysiwyf: What you see is what you pick. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2236–2244, 2012.

- [116] D. Wigdor, C. Shen, C. Forlines, and R. Balakrishnan. Table-centric interactive spaces for real-time collaboration. In *Proceedings of the working conference on Advanced visual interfaces*, pages 103–107. ACM, 2006.
- [117] B. T. Wilson, A. J. Lister, and R. I. Riemann. A nearest-neighbor imputation approach to mapping tree species over large areas using forest inventory plots and moderate resolution raster data. *Forest Ecology and Management*, 271:182–198, 2012.
- [118] C. A. Wingrave, Y. Haciahetoglu, and D. A. Bowman. Overcoming world in miniature limitations by a scaled and scrolling wim. In *3D User Interfaces, 2006. 3DUI 2006. IEEE Symposium on*, pages 11–16. IEEE, 2006.
- [119] M. Wohlfart and H. Hauser. Story telling for presentation in volume visualization. In *Proceedings of the 9th Joint Eurographics/IEEE VGTC conference on Visualization*, pages 91–98. Eurographics Association, 2007.
- [120] K. Wongsuphasawat, D. Smilkov, J. Wexler, J. Wilson, D. Mane, D. Fritz, D. Krishnan, F. B. Viégas, and M. Wattenberg. Visualizing dataflow graphs of deep learning models in tensorflow. *IEEE transactions on visualization and computer graphics*, 24(1):1–12, 2017.
- [121] Y. Yang, M. Cordeil, J. Beyer, T. Dwyer, K. Marriott, and H. Pfister. Embodied Navigation in Immersive Abstract Data Visualization: Is Overview+Detail or Zooming Better for 3D Scatterplots? *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1214–1224, 2020.
- [122] A. Ynnerman, T. Rydell, D. Antoine, D. Hughes, A. Persson, and P. Ljung. Interactive visualization of 3d scanned mummies at public venues. *Communications of the ACM*, 59(12):72–81, 2016.
- [123] A. Ynnerman, J. Löwgren, and L. Tibell. Explorantion: A new science communication paradigm. *IEEE computer graphics and applications*, 38(3):13–20, 2018.

- [124] L. Yu, K. Efstathiou, P. Isenberg, and T. Isenberg. Cast: Effective and efficient user interaction for context-aware selection in 3d particle clouds. *IEEE transactions on visualization and computer graphics*, 22(1):886–895, 2016.
- [125] S. Zhai, W. Buxton, and P. Milgram. The “silk cursor” investigating transparency for 3d target acquisition. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 459–464, 1994.
- [126] Z. Zhao, R. Marr, and N. Elmqvist. Data comics: Sequential art for data-driven storytelling. *tech. report*, 2015.

# Appendix A

## Details of Methodology

The collaborative storytelling framework described in Chapter 5 was used by a multi-disciplinary climate science research team. This appendix provides additional materials and details of the methodology.

### A.1 Installations (for a future trial with a larger group)

The desktop-client has several dependencies, e.g., a specific version of Python. Preparing for a future trial with a larger group, we provide an installation document detailing out steps of setting up those dependencies. To assist non-programmers, we also provide batch files that automate the processes of setting up the dependencies and installing the client.

### A.2 Logging Edits

A new user is asked to a username when he or she first opens one of our dedicated clients. As instructed in provided installation documents, a proper username is composed of user's name and device, e.g., "JungWho\_Android" or "Dan\_Mac". The username is associated with comments and edits made by the user using the device client. When the user creates a story or upload changes, V-Mail saves previous story files along with an upload time. In order to save a disk space,

it only saves files for storytelling and collaboration activities, such as the JSON file containing users' comments and drawing images; it does not save video files as these can be created after loading visualization stories from the saved files. By comparing to these multiple versions of the story files, we can figure out edits made in each iteration. By looking at all versions of a data story, we can figure out the numbers of edits, people involved, and different devices used in collaboration processes.

### **A.3 Pre-study and Post-study Questionnaires**

A pre-study questionnaire (A.3.1) is sent out to participants prior to the trial. It tries to access their demographic information, experience in data visualization, and current tools (and devices) for science-related communication and collaboration. The questions are divided into four parts: 1) general questions, 2) current approaches to science-related communication and collaboration, 3) current approaches of sharing visualization results with email-like communication tools, and 4) accessibility and choices of different devices for communication tasks. Questions from the second and fourth parts are multiple-choice questions: pick one or more from a given set of options. At the end of each section, a slot for optional feedback or comments is provided.

A post-study questionnaire (A.3.2) is sent out to participants after the trial. There are three parts: 1) open-ended questions of using V-Mail, 2) utility of specific software features, and 3) open-ended questions for future directions and feature requests. In the second part, we access usefulness of listed features or abilities for communicating 3D aspects of data, conveying correspondences between data views, collaborating with others, and in the mobile viewer. Participants are asked to rate these in a 5-point Likert scale.



### **A.3.1 Pre-study Questionnaire**

#### **1. General Questions**

1-1. What is your age?

1-2. What is your gender?

1-3. What is your field of expertise?

1-4. What is your level of experience (undergraduate, graduate, post-graduate or professional)?

1-5. How many years post-PhD (or equivalent) experience do you have in your field?

1-6. What best describes your role in this team science project? (climate scientist, simulation scientist, visualization designer, technologist, communications expert, general public audience, ...)?

#### **2. Approaches to communication and collaboration**

These are different approaches for collaborating around data visualization and the science behind it:

- a. In person
- b. Via a traditional phone call
- c. Over video conferencing
- d. By sending email-like messages about a subject
- e. By posting on a blog or on a social media site, e.g. Twitter and Facebook
- f. By doing PowerPoint-like presentations to audience

In the following questions, please tell us about the approaches you often take in the given situation. Please write down the associated letters to indicate the approaches. If you use other approaches not listed, please do specify them as well.

- 2-1. When timing is crucial, e.g. when you need a response right away
- 2-2. When answering a question in few words, e.g. stating an average temperature of a region
- 2-3. When you have open-ended questions that will probably go through multiple iterations of back-and-forth conversation
- 2-4. When the topic is complex that will take multiple steps to explain it properly
- 2-5. For describing different spatial features and structures in your data, e.g. showing the directions of ocean currents near a bay, and their significance to other parts of data
- 2-6. For communicating with overseas colleagues
- 2-7. For explaining science or your work to the public, e.g., stakeholders
- 2-8. For explaining science or your work to students in your class
- 2-9. (Optional) Any additional comments?

### **3. Email-style communication for 3D or 4D data**

- 3-1. Out of ten emails you recently sent back and forth with your colleagues, how many of these emails did include image(s), video(s), or visualization(s) that reveal

3D aspects of data?

3-2. Of the emails from 3-1, how many had visuals drawn with annotations or textual comments?

3-3. Of the emails from 3-1, how many did include project/scene files for recipients to reconstruct a shared visualization state for analysis or exploration?

3-4. (Optional) Any additional comments?

#### **4. Communication in different contexts on different devices**

4-1. How many hours of your day do you have easy access to these devices? You can write the hours next to each device. For example, since I work at a desk job, I would write 8 hours next to “Work PC”.

- Smartphone
- Tablet
- Personal laptop/PC
- Work PC
- Dedicated work simulation/visualization computation unit
- Augmented reality (AR)/ virtual reality (VR) head-mounted display(HDM)
- Projector-based/large screen display
- Other, please specify

4-2. How many times of your day do you use these devices for science-related communication? You can state one of these options next to each device: “multiple

times a day”, “1-2 per day”, “1-2 per week”, “1-2 per month”, “1-2 per year”, or “never”. For example, since I work at a desk job and collaborate with scientists from various domains, I would state “multiple times a day” next to “Work PC”.

- Smartphone
- Tablet
- Personal laptop/PC
- Work PC
- Dedicated work simulation/visualization computation unit
- Augmented reality (AR)/ virtual reality (VR) head-mounted display(HDM)
- Projector-based/large screen display
- Other, please specify

4-3. (Optional) Any additional comments?

### A.3.2 Post-study Questionnaire

#### 1. Open-ended Responses to Using V-Mail

1-1. How would you compare your experience communicating about data with V-Mail during this trial period to your typical experiences communicating about data? How was using V-Mail similar? How was it different?

1-2. Did you use the V-Mail URL link to share a V-Mail to others? If yes, why? If no, why not?

1-3. If yes, what platforms did you use to share it (e.g. email, Slack, blogs, social media)? And why did you choose the platform?

1-4. (Optional) Any additional comments?

#### 2. Utility of Specific Software Features

##### Rate the usefulness of these features or abilities

- Give a rating between 1 and 5, where 1 is very little useful and 5 is very useful.
- If you don't have any opinion, you can also mark it as such ("N.O.").

##### For communicating 3D aspects of data

2-1. Being able to draw on 3D views of data visualization

2-2. Being able to attach comments to 3D views of data visualization

2-3. Being able to see the 3D frames of data views floating in the same space of underlying data visualization

2-4. (Optional) Any additional comments?

**For conveying/viewing relations between shared 3D data views**

2-5. Being able to have animations connecting different data views

2-6. Being able to control the animation with a slider

2-7. The fact that the animation automatically stops between shots, i.e., that the story is split into parts.

2-8. Being able to play an animation backwards

2-9. (Optional) Any additional comments?

**For collaborating with others**

2-10. Having the ability for others to edit your own V-Mail, e.g., adding new data views or comments

2-11. Being able to leave comments directly on the 3D views shared by others

2-12. Being able to use the URL as a distribution mechanism

2-13. Being able to have a web-page with a video file of a created message

2-14. Being able to open the link with our custom mobile or desktop application

2-15. (Optional) Any additional comments?

### **About the mobile viewer**

2-16. Did you use the mobile viewer? Yes or No

2-17. If yes, what do you think the expected time will be for someone new to learn to use this mobile application?

2-18. If yes, did you use the 360 viewer on the mobile device? Yes or No

2-19. (Optional) Any additional comments?

### **3. Help inform the future**

3-1. Do you expect to continue to use V-Mail in your communications about data?

3-2. If we were to add or change one feature of the software, what would it be and why/details?

3-3. (Optional) Any additional comments?