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ST^{2}VR: An Interactive Authoring System for SpatioTemporal STorytelling in Virtual Reality with Hierarchical Narrative Structure

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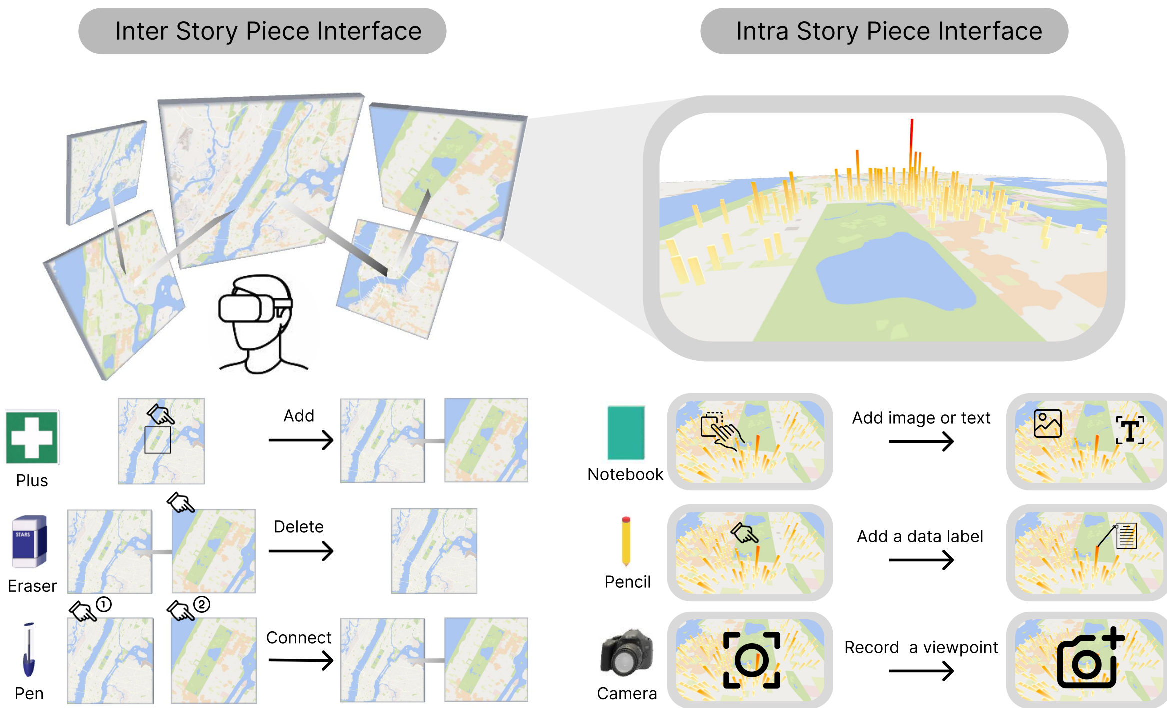

Figure 1: Our immersive system for authoring spatiotemporal data story, ST^{2}VR, consists of two interactive interfaces: the inter story piece interface and the intra story piece interface. The inter story piece interface supports the creation, deletion, editing, and organization of story pieces. The intra story piece interface allows for detailed design of text, images, data labels, and viewpoints within story pieces. These two interfaces enable our system to support spatiotemporal data story authoring at different levels, from managing the overall narrative to designing story details.

Abstract

The increasing popularity of Virtual Reality (VR) has provided a new medium for narrating spatiotemporal data stories. Compared to traditional 2D environments, telling spatiotemporal stories in VR holds the promise of offering a more immersive and engaging experience for audiences. However, when creating VR spatiotemporal data stories, story creators may feel overwhelmed by the numerous narrative elements involved and there is a disconnect between the creation and viewing environments. To address these challenges, we designed a hierarchical narrative structure with three levels: Story Line, Story Piece, and Viewpoint. We then introduce ST^{2}VR, an interactive authoring system that supports the creation of spatiotemporal data stories within an immersive environment. The system features two types of interactive interfaces to support the organization of the overall narrative as well as the immersive design of story details. A use case demonstrates the process of authoring VR spatiotemporal data stories using ST^{2}VR, and a user study evaluates the system's efficiency and effectiveness.

Keywords: Immersive Storytelling, Authoring System, Spatiotemporal Data

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1 Introduction

A spatiotemporal data story integrates both spatial and temporal data to reveal trends, patterns, or events across space and time [41]. The narrative helps communicate insights into complex phenomena, such as urban traffic [23] and climate change [57], by visualizing how data evolves over time in specific geographical areas and telling compelling stories. However, most of these stories are limited to two-dimensional and non-immersive displays [18, 19, 39], restricting the viewer's ability to fully grasp the inherent three-dimensional

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characteristics of the data [14]. With rapid advancements in virtual reality (VR) technology and the increasing accessibility of immersive devices, integrating VR into spatiotemporal data storytelling has increasingly gained attention. Presenting spatiotemporal data stories in immersive environments offers the potential for a more engaging and interactive experience, as demonstrated by its success in spatiotemporal education [51], 3D simulations in gaming [31], and urban planning initiatives [30].

However, authoring immersive spatiotemporal data stories presents two major challenges for story creators. First, story creators may feel overwhelmed by the numerous narrative elements involved [15], such as narrative sequence, hierarchy, scale, context, and visualizations. Second, there is a disconnect between the authoring and viewing environments. Current authoring tools for spatiotemporal data stories are primarily designed for non-immersive, two-dimensional platforms [35, 36], forcing story creators to build immersive experiences within non-immersive interfaces. This mismatch makes it difficult for creators to accurately predict how their stories will be experienced by the audience in the immersive environment, not to mention precisely control the audience's viewing experience and ensure an engaging, seamless narrative.

In order to address the first challenge, we proposed a three-level hierarchical narrative structure, to assist creators in narrating spatiotemporal data stories. The hierarchical narrative structure includes *Story Line*, representing the overall narrative of the spatiotemporal data story, *Story Piece*, corresponding to the narrative segment for the specific spatiotemporal scene, and *Viewpoint*, the specific and captured camera pose within the story piece. Also, we considered interpolated transitions between story pieces and viewpoints during the story presentation to enhance the coherence of the narrative. To address the second challenge, we developed ST^{2}VR, An immersive spatiotemporal story authoring system guided by the hierarchical narrative structure. To meet the requirements of story creators for controlling the overall narrative as well as immersively designing the story details, ST^{2}VR consists of two interactive interfaces (Fig. 1): the inter story piece interface and the intra story piece interface. The inter story piece interface supports the creation, deletion, and organization of story pieces to form a cohesive story line. The intra story piece interface allows for detailed design of text, images, and data labels within story pieces, as well as immersive selection of viewpoints for storytelling. To address the requirements of spatiotemporal data visualization, ST^{2}VR includes three types of visualizations: 3D heatmaps, 3D histograms, and 3D scatter plots. Story creators can choose data visualization types based on data characteristics and narrative needs, effectively conveying their ideas to the audience. We evaluated the efficiency and effectiveness of ST^{2}VR through a usage scenario and a user study. Overall, our hierarchical narrative structure and authoring system assist story creators in authoring immersive spatiotemporal data stories more effectively. The main contributions of our work are summarized as follows:

- **A hierarchical narrative structure for authoring spatiotemporal data stories**. It comprises three narrative levels in a top-down fashion: story line, story pieces, and viewpoints, allowing for structured control of the narrative at different levels of granularity.
- **ST^{2}VR, an interactive authoring system for spatiotemporal data stories in VR**. Following the hierarchical narrative structure, our system supports editing and connecting different levels of the story. This allows for narrative construction and organization, enhancing both the creative process and the coherence of the story.
- **A user study to evaluate the effectiveness and efficiency of our system**. We implemented a non-immersive counterpart of ST^{2}VR and conducted a user study to compare it with ST^{2}VR. The comparative study provided insights into the performance of our immersive authoring system.

2 Related Work

This section discusses the methodologies for data storytelling within the context of spatiotemporal data and immersive environments. We summarize the related work about data storytelling, authoring spatiotemporal narratives, and immersive storytelling.

2.1 Data Storytelling

Data stories consist of a sequence of story segments presented in a specific format to convey intended information [34, 48]. Research indicates that applying data visualization to storytelling can effectively reveal and communicate insights [24] and enhance reader engagement, understanding, and communication [9, 20]. Thus, visual data storytelling has gained increasing attention across various fields and its importance within the visualization domain is growing [32]. Several narrative frameworks and techniques for data storytelling have been proposed. In a design space analysis of 58 narrative visualizations, Segel et al. [55] categorized narrative visualizations into seven types and summarized three narrative structures. McKenna et al. [43] identified seven key factors for constructing a smooth visual narrative flow, while Stolper et al. [62] introduced four important narrative visualization techniques. Based on these narrative theories, existing research has proposed authoring tools for data storytelling.

Chen et al. [12] were among the first to introduce the concepts of story segments and story composition. They proposed a generic framework for story composition, which involves selecting, assembling, and arranging story segments into a meaningful layout. Sun et al. [63] developed a human-computer collaborative data story authoring system that generates insightful and coherent data stories by automatically interpolating between themes and structures. While these works address the coherence of data stories, the resulting stories are constrained to a static layout. Amini et al. [2] proposed an authoring tool designed to lower the barriers to producing data story videos, allowing non-experts to assemble data-driven story segments into longer sequences. These authoring tools primarily involve two-dimensional visual graphics and are not suitable for three-dimensional scenes. Li et al. [36] derived a design space for camera movements and developed an interactive tool that allows users to flexibly design camera movements for creating geographic data stories. This work focuses on narrative perspective transitions, neglecting the interactive design of story content and the consideration of different geographic scales. Our work further considers managing multiple scenes with different spatiotemporal attributes, where each scene contains three-dimensional features as well as visual elements such as text, images, and data labels, forming a cohesive data story.

2.2 Authoring Spatiotemporal Narratives

Spatiotemporal narratives combine space and time dimensions to craft stories that help users understand complex processes or phenomena unfolding over time within specific spatial contexts [41]. By combining data visualizations with storytelling techniques, spatiotemporal narratives make complex data more digestible [42]. In recent years, the rapid advancements in technology and data collection have led to a surge in the use of spatiotemporal data visualization tools [4, 6, 54, 66]. TaxiVis [23] presents a method for visualizing a large amount of New York taxi data with both spatial and temporal dimensions and examining taxi usage trends at different time granularities. In order to better help developers analyze and explore spatiotemporal data, Li *et al.* developed a semi-automatic data tour user interface [35] to help explore complex networks based on city maps. Research shows that map-based authoring tools reduce the creator's exploration effort and help disseminate analysis results. Based on the increasingly mature visualization techniques, spatiotemporal narratives have become an increasingly powerful tool in many fields, especially journalism [58]. Narrative strategies like sequential guidance, slides, or flow charts can typically enhance the relevance and effectiveness of data-driven stories to different extents [56]. *The New York Times* created a spatiotemporal visual story to illustrate climate changes and convey the urgency of sustainable development [57]. The spread of COVID-19 was displayed in map-based visualizations, and users could explore interactively to deeply understand the story [1].

The growing demand for personalized data stories has drawn researchers' attention to the development of authoring tools [64, 69]. Calliope [59] supports automatically generating visual data stories from spreadsheets. Existing works have focused on authoring spatiotemporal storytelling. GeoTime [21] firstly enhanced spatiotemporal event visualization tool with a story system integrating narrative strategies. Lundblad *et al.* [40] promoted analytical reasoning by combining innovative visualization of geographic and dynamic data with storytelling. GeoCamera [36] facilitates crafting camera movements for spatiotemporal data videos. However, authoring spatiotemporal narratives in the VR environment remains blank in the current research field. Our work is the first to provide creators with an authoring tool for spatiotemporal storytelling in an immersive environment through immersive interactions.

2.3 Immersive Storytelling

Immersive visualizations have permeated various facets of our lives, extending beyond gaming to include health, education, urban planning, training, and simulations [76]. Despite the widespread adoption of immersive visualization techniques and AR/VR technologies, immersive storytelling has received comparatively less focus. Immersive storytelling is a narrative technique that deeply engages audiences by placing them inside the story through head-mounted display devices [10, 74]. Compared to traditional narrative approaches, immersive storytelling can significantly enhance user engagement [75] and stimulate empathy [27]. Chopra *et al.* [13] uncovered that interaction with story characters provides users with a sense of being fully immersed in the environment. The growing prevalence of AR/VR devices in data visualization and analysis [28, 67, 78] presents a timely opportunity to explore their integration into immersive storytelling. As highlighted by Yang [77], immersive environments offer a uniquely expansive and novel platform for narrative exploration, underscoring the vast potential of immersive storytelling for future applications, such as education [17], nursing training [25], and museum guidance [65].

Existing works have conducted exploratory research about immersive storytelling with AR/VR devices. Isenberg [29] introduces "immersive storytelling" as an experience characterized by profound absorption, leading to deep involvement, engagement, and captivation with the data. Romat *et al.* [49] utilized pictographs (comprising multiple data glyphs) to showcase a personalized approach to immersive storytelling, aimed at enhancing enjoyment and engagement. In a similar vein, Lee *et al.* [33] introduced the concept of visceralization, enabling users to interactively explore a VR environment and experientially engage with data—such as sensing the pace of runners, viewing the Eiffel Tower from various angles in a real-world scale, or observing a protest from multiple perspectives. Zhu *et al.* [78] investigated how different data representations and embodied interactions of an immersive data story influence people's situational awareness. These examples highlight diverse approaches to crafting immersive storytelling in AR/VR environments. Nonetheless, few have specifically addressed immersive storytelling involving spatiotemporal data. Alternative methods, like the Datahop system, which facilitates free movement within a virtual environment and narrative navigation [26], provide valuable inspiration. Our work unifies the story authoring environment with the immersive story presentation environment and supports different levels of immersive visualizations and interactive functions, to enhance the efficiency of story authoring and the expressiveness of the data story.

3 Design Consideration

Our work aims to assist creators of immersive spatiotemporal data stories in the authoring process. To achieve this, we conducted semi-structured interviews, each lasting approximately 30 minutes, with three data story creators (C1-C3). The three creators have varying experiences of data visualization and storytelling. C1 works on data storytelling and data video generation, C2 specializes in spatiotemporal data visualization and visual analytics, and C3's expertise lies in immersive visualization and immersive analytics in virtual reality. All these creators have experience in authoring data stories. We gathered insights from creators regarding the requirements for authoring data stories, progressively narrowing the conditions to spatiotemporal data scenes and immersive environments. The goal of the interviews was to understand the current practices and challenges faced by data story creators from different related fields, gather common requirements for creating spatiotemporal data stories, and collect insights into story authoring within immersive environments.

We selected two different spatiotemporal data stories for the interview. The first, from The Pudding, illustrates the population distribution and changes in major cities around the world from 1990 to the present. The second, by Esri's StoryMaps team, tells the story of a rescue team aiding stranded climbers in a spatiotemporal data context. The creators were asked to view these stories on a screen and then describe how they would approach authoring these stories as story creators. They also discussed how they would improve the authoring process in an immersive environment to better facilitate storytelling. Based on our interview results, we have distilled the following design goals:

Supporting both overall narrative management and detailed story design (G1). The creators emphasized that creating a spatiotemporal data story requires controlling the story's trajectory from a macro level to ensure narrative coherence, while also focusing on the details to enhance storytelling effectiveness. C1 mentioned, *"I'd like to first mark the key spatiotemporal scenes of the story, then consider how to transition between them."*, C3 suggested, *"I'd prefer to immerse myself in the scene from a first-person perspective, as that helps capture more impactful shots."* These insights inspired us to offer multiple interactive interfaces for story creators. One interface should provide a broad workspace to manage the overall narrative of the story, supporting both viewing and editing of the entire narrative's flow. Another interface should allow story creators to observe and design specific content within spatiotemporal scenes through an immersive perspective.

Supporting multiple spatial and temporal scales, visualization types, and visual elements (G2). In spatiotemporal data storytelling, creators often need to present stories with varying time spans and spatial scales. C1 mentioned, *"Sometimes I want to show the frequency distribution of data over a large geographic region for a long time period, while other times I want to depict a scatter plot of events within a small area over a short time span."* C2 highlighted the need to *"flexibly use different types of visualizations depending on the situation, such as heatmaps, scatterplots, etc."* Therefore, our tool needs to enable story creators to control the time span and spatial scale of each story segment and provide a range of commonly used visualization types for spatiotemporal narratives, along with other essential visual elements.

Supporting automatic transitions between story segments with different spatial and temporal properties (G3). In spatiotemporal stories, the transition between segments with different spatial and temporal properties needs to be smooth to ensure a coherent and natural narrative flow. For example, in the first story we presented to the creators, the transition between a description of population distribution in San Francisco, USA, and Hong Kong, China, involved zooming and panning across the map. C1 noted, *"I think natural transitions between different scenes are essential, otherwise it's easy to get lost in the story and hard to understand the logical connections."* C2 stated, *"Such transitions are necessary, and I'd like to accomplish them with the simplest and most time-efficient operations possible."* Therefore, our system should automatically manage transitions in time, space, and perspective between different story segments, improving narrative coherence and enhancing the viewer's experience.

Supporting intuitive and user-friendly authoring in an immersive environment (G4). All three creators agreed that presenting spatiotemporal data stories in an immersive environment is meaningful. C3 mentioned, *"The wide field of view in an immersive environment offers a level of visual impact that desktop displays can hardly match."* Regarding authoring in an immersive environment, C2 said, *"Authoring a VR story in a desktop environment is challenging because the inconsistency in environments makes it difficult for creators to control the viewer's experience accurately."* Therefore, we believe that researching story authoring in immersive environments is valuable. Additionally, in terms of interaction within the immersive environment, C3 emphasized, *"Interactions in immersive environments should be intuitive and user-friendly enough to reduce the cognitive load on the story creator."*

4 Hierarchical Narrative Structure

A visual data story is a sequence of interconnected data presented in the form of narrative visualization [34]. Story creators need to design the data visualization they wish to present, link them logically, and ensure smooth transitions, ultimately forming a cohesive and comprehensive visual data story. A well-structured visual data storytelling authoring framework can assist creators in efficiently completing this authoring process. Previous works [12, 63] have decomposed visual data stories into multiple independent story seg-

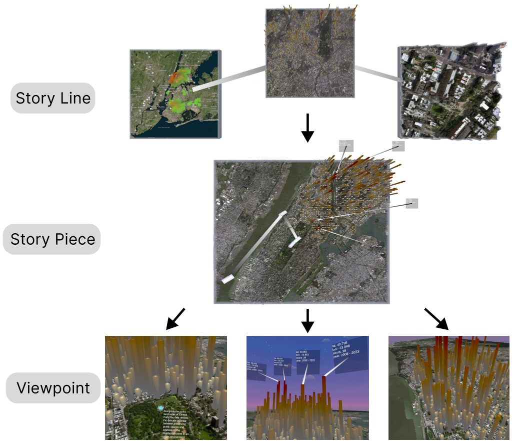


Figure 2: We proposed a three-level hierarchical narrative structure which consists of three levels, arranged from top to bottom: story line, story piece, and viewpoint. This hierarchical narrative structure supports spatiotemporal data authoring at different levels, from managing the overall narrative to designing story details. The transitions between story pieces and viewpoints connect these elements into a coherent narrative.

ments and studied how to combine or connect these segments to form a complete story. However, such frameworks are designed for data stories composed of static 2D visual graphics, making them unsuitable for spatiotemporal data stories that involve dynamic transitions and 3D data scenes.

In this study, to help story creators better observe, edit, and organize narrative content during the authoring process and improve the coherence of the story, we propose a hierarchical structure for authoring spatiotemporal data stories based on the design requirements collected in Sec. 3. This structure adopts a top-down approach and consists of three narrative levels (Fig. 2): Story Line, Story Piece, and Viewpoint. It also supports smooth transitions between story pieces and viewpoints.

4.1 Narrative Structure

Our proposed three-layer narrative structure consists of story Line, story piece, and viewpoint, which together help story creators maintain control over both the macro-level direction and the micro-level details of their narrative **(G1)**. We primarily focus on author-driven narratives, where the progression is entirely determined by the creator, making the story strictly linear [55]. Using this narrative framework, creators can first conceptualize the main themes and narrative flow (Story Line), then select key spatiotemporal scenes for the narrative (Story Pieces), and finally, design each story piece in detail by defining the key perspectives for the audience (Viewpoints). This top-down narrative structure enables creators to systematically create spatiotemporal data stories.

Story Line. In our proposed framework, the story line is represented as a linear sequence of spatiotemporal scenes connected in the order of the narrative. Creators can reorganize, add or remove story pieces, and thus maintain control over the narrative's flow.

Story Pieces. This concept emphasize the hierarchical relationship between the overall storyline and specific spatiotemporal scenes. Each story piece corresponds to a specific spatiotemporal scene within the story. Creators can define the spatial and temporal boundaries of each story piece, add various types of data visualizations, and incorporate other visual elements **(G2)**. To enable a more detailed design process, our framework supports the creator's ability to immerse themselves in each spatiotemporal scene from a first-person perspective during the story piece design phase.

Viewpoints. Viewpoints represent specific camera positions within a spatiotemporal scene. The sequential arrangement of viewpoints within each story piece dictates the camera's movement as the audience views the story. Creators can explore each scene from a first-person perspective to identify suitable viewpoints, ensuring that the desired visual frames are directly conveyed to the audience.

4.2 Narrative Transitions

In spatiotemporal data stories, the transition between different scenes and camera positions is important for maintaining narrative continuity, which helps the audience better experience and comprehend the story. In our framework, we consider two types of transitions: between story pieces and between viewpoints. Through these two types of interpolation-based transitions, the generated story consists of smooth animations involving the movement between spatiotemporal scenes and the continuous motion of the camera **(G3)**.

Transitions between Story Pieces. For transitions between adjacent story pieces along the story line, we interpolate the spatial and temporal properties between the corresponding spatiotemporal scenes. This ensures a seamless progression from one story piece to the next, allowing for natural shifts in both space and time.

Transitions between Viewpoints. We focus on transitions between two adjacent viewpoints within the same story piece, as well as between the final viewpoint of one story piece and the initial viewpoint of the next. Interpolation is used to create smooth camera motion between these viewpoints, enabling continuous changes in camera position and orientation. This enhances the fluidity of the narrative, providing a more immersive experience for the audience.

5 ST^{2}VR

In accordance with our proposed authoring framework for spatiotemporal data stories and the corresponding requirements in Sec. 3, we have developed ST^{2}VR, an immersive system that empowers the story creator to create spatiotemporal data VR stories following the hierarchical narrative structure.

5.1 System Overview

In ST^{2}VR, we have implemented the organization of story pieces as well as the design within each story piece **(G1)**. To support the aforementioned functionalities, ST^{2}VR has two interfaces: **inter story piece interface** and **intra story piece interface**. ST^{2}VR simultaneously supports different types of spatiotemporal data visualizations, external structural relationships between story pieces, and the immersive viewing and design of story details within each story piece. To facilitate user creativity at different levels and follow the hierarchical narrative structure, we designed a series of interactions, which are divided into two categories: inter story piece interactions and intra story piece interaction.

5.2 Visualization Design

In the VR environment, the story creator benefits from an expansive field of view and multiple surrounding views, which streamline the observation of spatiotemporal information across different regions [52]. To leverage this advantage, we construct a story line by manipulating multiple story pieces in virtual space. The Assets associated consists of the map layer, spatiotemporal data visualization, and narrative elements such as text, images and 3D models. Data and other assets are pre-stored in the system's resources. Story creators can select the assets they need for the story to be created through the inspector panel before the system launches, and data for each story piece can be switched using the controller during the authoring process.

5.2.1 Data Visualization Design

ST^{2}VR supports different types of spatiotemporal data visualizations within story pieces to meet narrative requirements **(G2)**. To enhance the expressiveness of data visualizations, we incorporate 3D visualizations onto the story pieces [72]. In the 3D space within each story piece, the three axes represent longitude, latitude, and value, respectively. We primarily focus on three types of spatiotemporal visualizations: 3D heat maps, 3D histograms, and 3D scatter plots. The 3D heatmap appears as a terrain-like effect on the map, conveying the coarse-grained distribution characteristics of the spatiotemporal data. The 3D histogram provides a finer-grained representation of the data values corresponding to each geographic coordinate. In the 3D scatterplot, 3D models representing data points are distributed throughout the story piece, with the size and height of the points encoding data values and temporal information.

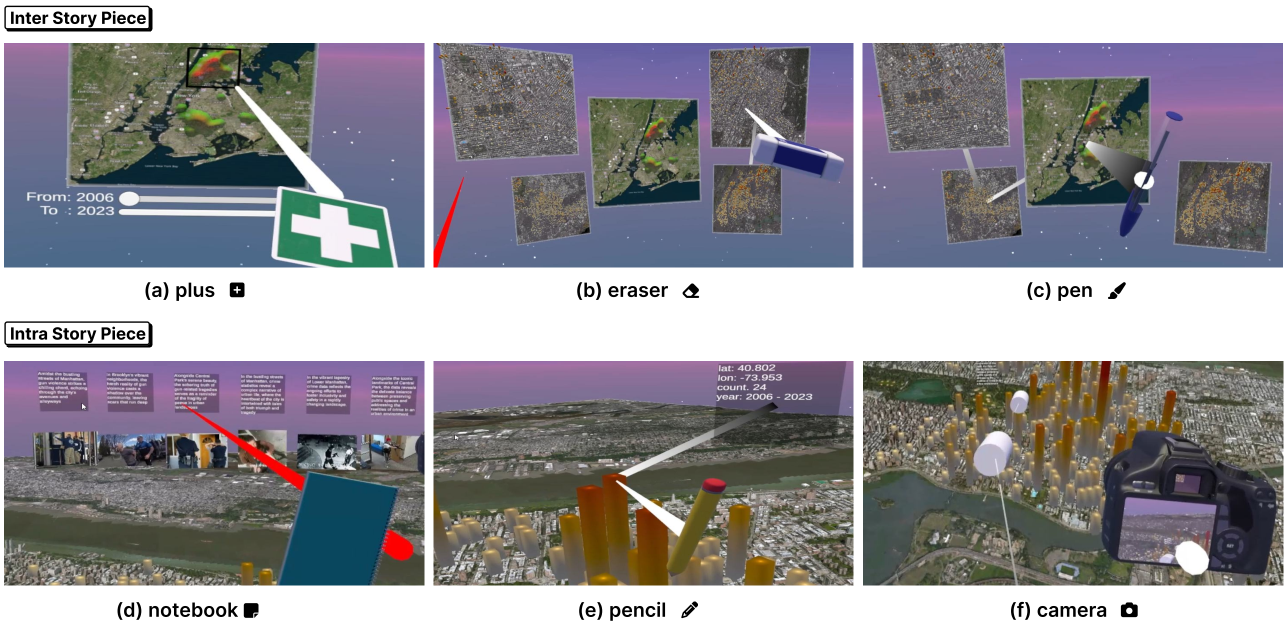


Figure 3: **ST^{2}VR incorporates six tool-based interactions:** (a) The "plus" tool, which enables generating new story pieces based on existing ones. (b) The "eraser" tool, facilitating the removal of story pieces or connections between story pieces. (c) The "pen" tool, allowing connections between story pieces. (d) The "notebook" tool, supporting the addition of text or image content to story pieces. (e) The "pencil" tool, used for adding data labels to specific locations in story pieces. (f) The "camera" tool, designed for recording viewpoints within story pieces. Among these, tools (a), (b), and (c) are utilized for editing between story pieces, while tools (d), (e), and (f) are employed for design within each story piece.

5.2.2 Inter Story Piece Visualization Design

In ST^{2}VR, story pieces are represented as "map blocks" that contain the temporal and spatial information, data visualizations, and viewpoints. In the system interface, multiple story pieces are laid out in front of the story creator, connected to form the story line. ST^{2}VR provides a spacious workspace within a virtual environment, allowing users to easily observe multiple story pieces simultaneously and edit and organize the pieces according to narrative needs **(G1)**.

5.2.3 Intra Story Piece Visualization Design

ST^{2}VR supports an immersive perspective within each story piece. The system enlarges the size of the story piece, placing the creator inside the story piece as the central focus. This creates a sense of immersion in a real spatiotemporal scene, enhancing the creator's experience of immersion [22]. It allows the creator to observe and design the content within the story piece more effectively from a first-person perspective. To enrich the data story and improve its comprehensibility, the system allows embedding data labels, text, and image information within the story piece **(G2)**.

5.3 Interaction Design

To support the design of different levels of story authoring following the hierarchical narrative structure while reducing memory load **(G4)**, ST^{2}VR provides a series of virtual tools-based interactions (Fig. 3). These interactions are divided into two categories: inter story piece interactions and intra story piece interactions. The former supports the organization of story pieces to form the story line, while the latter facilitates design within a single story piece.

5.3.1 Inter Story Piece Interaction Design

Following the hierarchical narrative structure, ST^{2}VR supports editing the relations between story pieces through inter story piece interactions to connect them into the story line. The story creator can generate or delete story pieces and modify their sequence, assembling the story line by connecting multiple story pieces. To immerse the story creator in the authoring process, we have introduced the physical collision characteristics of story pieces themselves during interaction with them [45]. We provide the following interactions for editing and organizing story pieces:

Move and Adjust Story Pieces. To support the story creator in arranging story pieces, ST^{2}VR allows using controllers to select specific story pieces for adjusting their visualization types, temporal attributes, spatial attributes, sizes, and map zoom levels. The spatiotemporal data within the Story Piece will be updated accordingly.

Create Story Pieces. We need to support creating new story pieces based on existing ones. By grabbing the " plus" tool, the story creator can create a new story piece by outlining a rectangular area on the existing story piece (Fig. 3.a). The new story piece's spatial property correspond to the selected rectangular region. When this interaction is activated, a slider UI appears below the story piece, allowing control over the temporal property of the story piece.

Delete Story Pieces. With the " eraser" tool in hand, the story creator can delete connections between story pieces by clicking the lines connecting them (Fig. 3.b). Alternatively, the story creator can delete a story piece by clicking the story piece itself.

Connect Story Pieces. To facilitate the construction of the story line, the story creator can interactively connect two story pieces in addition to generating linked story pieces directly from creating new story pieces. The story creator can establish a connection between two story pieces by using the " pen" tool to click both story pieces successively (Fig. 3.c). A connecting line appears between two story pieces to indicate their sequence in the story line.

Enter Story Pieces. ST^{2}VR supports switching between inter story piece interface and intra story piece interface. By clicking on a story piece with a controller, story creators can enter the story piece, immersing themselves in the spatiotemporal scene.

5.3.2 Intra Story Piece Interaction Design

ST^{2}VR supports an egocentric immersive perspective for authoring within the story piece. Immersed in a story piece, story creators find themselves positioned between the spatiotemporal scene and visualized data, observing them from an egocentric perspective. To enable the story creator to freely explore suitable narrative perspectives and design content within the story piece, ST^{2}VR allows the story creator to navigate within the story piece using controllers, with the ability to rotate their headsets to adjust their viewing angle. We implemented the following interactions to assist the story creator in designing the content within the story pieces.

Record Viewpoints. By grabbing the " camera" tool and triggering a "record" through controller buttons (Fig. 3.d), the story creator can record a viewpoint at the current location and viewing angle, capturing spatiotemporal data and any added contents in view.

Add Data Labels. ST^{2}VR supports precise data value display. Using the " pencil" tool, the story creator can select a point within the story piece and add a data label to display the corresponding information (Fig. 3.e). The position and scale of the labels can be adjusted using the controller's drag and button functions.

Add Text or Image Content. ST^{2}VR supports enhancing reader comprehension by adding text or image content to aid in understanding the story. By grabbing the " notebook" tool and selecting pre-prepared text or image content (Fig. 3.f), the story creator can drag and drop the content into the appropriate position within the story piece. The position and scale of the visual content can be adjusted using the controller's drag and button functions.

Exit Story Pieces. the story creator can exit the intra story piece interface of the current story piece by performing a "backward" action, returning to the inter story piece interface. After exiting, the story creator can see thumbnail representations of viewpoints, text and image content, and data labels within the story piece.

5.4 Story Presentation

Once the story is created, it can be presented to the audience. Throughout the authoring process, ST^{2}VR records the spatiotemporal scenes and observational viewpoints through story pieces and viewpoints. When selecting to preview the story using the controller, ST^{2}VR automatically performs interpolated transitions between the spatiotemporal scenes and the recorded viewpoints **(G3)**, forming a linear structure for the spatiotemporal data story. The audience can experience the story along this linear structure and use the controller buttons to switch to the next viewpoint or rewind to the previous one, immersing themselves in the story conveyed by the story creator.

6 Usage Scenario

We illustrate the process of authoring a spatiotemporal data story through a use case (Fig. 4). We will tell a story about shooting incidents in New York City. The spatiotmporal data we used consists of the shooting incidents in New York City from 2006 to 2022.

Design of Story Pieces. Firstly, we need to envision which story pieces are required to form the story line. We progress the story gradually by designing a story line from the macro to micro level. The first story piece encompasses the entire New York City scene, where we can have an overview of the overall situation of shooting incidents in the city. To delve deeper into the shooting incident frequency in various regions of New York, we use the "plus" tool to sequentially select three different areas on the first story piece and control the time slider to create three new story pieces. Our story will introduce the data distribution in these three areas one by one (Fig. 4.a). Then, we select a smaller local area within one of the regions to generate a new story piece representing the neighborhood scene range. Next, we connect the story pieces in sequence by drawing lines using the "pen" tool to form the complete story line (Fig. 4.b). Any extra or undesired story pieces or connections can be removed using the "eraser" tool.

Design within Story Pieces. In each story piece, we conduct more detailed story design, including choosing the proper type of visualization, adding data labels using the "pencil" tool, adding text content using the "notebook" tool, and recording viewpoints using the "camera" tool. Within the story piece representing the entire New York City, we choose 3D heat map to visualize the data and record a series of spiraling downward viewpoints to observe the 3D visualization of shooting incidents (Fig. 4.c). In the subsequent story pieces for different regions of New York City, we utilize 3D histograms to present a more granular distribution of the data, label the peak points of shooting incidents in that area and add corresponding descriptive text (Fig. 4.d). In the story piece depicting street scene, we choose the 3D scatter plot with bullet models to visualize specific shooting incidents, add relevant images, and record immersive viewpoints for observing shooting incident information on city streets.

Story Presentations. Audiences will witness the following effects. Firstly, they will experience a spiraling descent of viewpoints, allowing them to observe the complete city data from multiple angles. Subsequently, the viewpoints will leap to various areas of the city, presenting textual descriptions and peak points of shooting incidents in each area. Finally, the viewpoint will enter street scenes within the city, where audiences can observe specific information about shooting incidents among city buildings.

We demonstrate how to use ST^{2}VR for authoring a spatiotemporal story through this case. The story creator can design the story from a top-down approach: first conceptualizing the overall structure and direction, then focusing on the details of each spatiotemporal scene. Using the inter story piece interface and the intra story piece interface, the creator can manage the overall composition and the design of each story scene, while selecting the camera positions for viewing the story from an immersive perspective.

7 User Study

To evaluate of the efficiency and effectiveness of ST^{2}VR, we compared it to its non-immersive counterpart, which is also the current best practice for creating an immersive experience. By keeping the story authoring structure consistent and using the authoring environment as a variable, the controlled variable study aimed to investigate the relative pros and cons of immersive versus non-immersive authoring experiences supported by a suitable and consistent narrative structure, to inform the design of future authoring tools.

7.1 The non-immersive counterpart of ST^{2}VR

Similar to our immersive spatiotemporal data story authoring tool, the desktop version also focused on spatiotemporal data stories. We intentionally provided identical features in the desktop version, as we were primarily interested in the effects of display and interaction affordances between the computing environments (VR vs. desktop), rather than functionality differences. Consequently, the desktop version also employed the hierarchical narrative structure with inter story and intra story interfaces. All interactions and functionalities were appropriately adapted for the desktop environment. Representative adaptations, particularly how we support the spatiotemporal story authoring, are illustrated here.

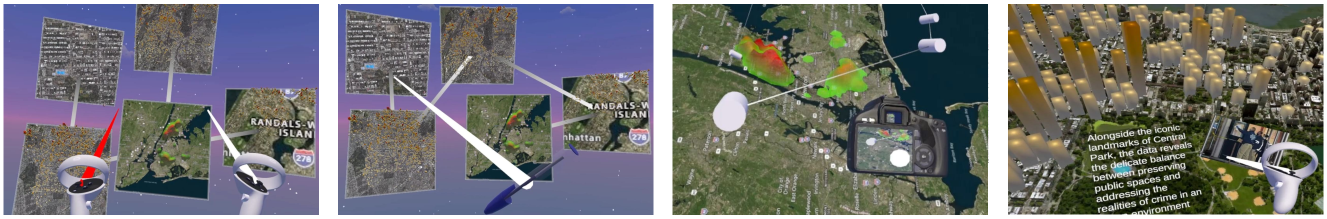
Inter Story Piece Interface. Inspired by previous work [28], an infinite canvas was used as the workspace for placing and interacting with story pieces. The infinite canvas on the desktop mirrored the large display space in VR, enabling zoomable navigation to address the limited physical screen space. This concept has been widely adopted in creative tools like Miro, Jamboard, Whiteboard, and SAGE. In the workspace, participants could freely place story pieces and zoom in/out. Additionally, the tool-based interactions for story pieces in VR (move, adjust, create, connect, delete, enter) were adapted to mouse interactions (Fig. 5.a).

Intra Story Piece Interface. On the desktop, we also embrace an egocentric immersive perspective for internal authoring within the story piece. Story creators navigate this space by rotating their viewpoint with mouse movements and moving in different directions using keyboard (WASD) inputs. This navigation interaction adheres to the widely accepted approach for first-person perspective implementations, such as AutoCAD and Unity3D. Similarly, the intra story interactions in VR (adding text or image content, adding data labels, recording viewpoints, and exiting a story piece) were adapted to mouse interactions (Fig. 5.b).

7.2 Participants

Our target users are individuals without a strong technical background. Therefore, we recruited 16 students (8 undergraduates, 4 master's students, and 4 PhD students) from a local university, who had no experience in immersive application development.

The gender distribution consisted of 6 females and 10 males, with an average age of 20.75 years and a standard deviation of 1.24. All participants had either normal vision or vision corrected to normal standards. Among them, 4 reported occasional use of VR technology, while the remaining individuals reported no experience with VR.



(a) (b) (c) (d)

Figure 4: **In the usage scenario, an immersive spatiotemporal data story is created through the following steps:** (a) Using the " plus" tool to generate multiple new story pieces from existing story pieces, to initialize the scenes required for the story line. (b) Reordering the connections between story pieces and adjusting the narrative sequence using the " eraser" and " pen" tools. (c) Recording a series of spiraling descent viewpoints using the " camera" tool to design the route of viewpoint transition. (d) Adding text, image content, or data labels to the interior of story pieces using the " notebook" and " pencil" tools.

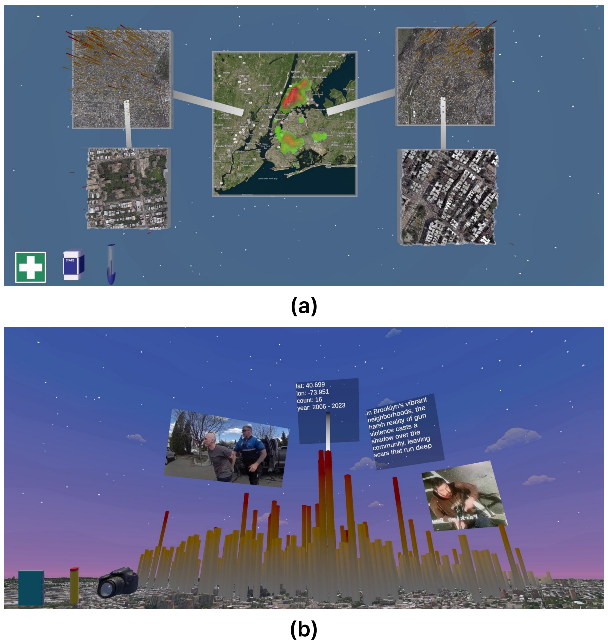


Figure 5: The interfaces of ST^{2}VR's non-immersive counterpart include (a) The inter story piece interface on desktop. (b) The intra story piece interface on desktop. Apart from the difference of the environments, the interactive interface setup of the desktop system is identical to that of ST^{2}VR.

7.3 Experimental Setup

For the VR condition, we utilized the Meta Quest 2 virtual reality headset, boasting a per-eye resolution of 1920 × 1832 and a refresh rate of 90 Hz. In contrast, the desktop environment featured a 27-inch monitor with a resolution of 2560 × 1440 and a refresh rate of 75 Hz, representing a standard office setup. In both scenarios, the computer systems were equipped with an Intel i5-13400F processor and an NVIDIA GeForce RTX 3060 Ti graphics card. We employed a streaming setup where computations were performed on a PC, while rendering was handled by the VR headset. In the VR setting, our study took place within a 2 x 4-meter (8 square meters) space, allowing participants the freedom to move around. Participants started each VR session positioned at the center of the physical space. In the desktop environment, participants sat comfortably in an office chair with the monitor placed on a desk in front of them. In both VR and desktop conditions, we placed an initial map containing spatiotemporal information at the center of their field of view. The spatiotmporal data we utilized in our study consist of arrest incidents and shooting incidents in New York City from 2006 to 2022.

7.4 Study Tasks

We aimed to evaluate the user experience and performance associated with two distinct authoring processes: a controlled authoring process, primarily focused on evaluating efficiency, and an open-ended authoring process, which emphasized evaluating experience and outputs. We introduced our hierarchical narrative structure and systems, along with the goals of our experiment, to the experts from the previous interview. With their help, we designed two separate tasks, each specifically tailored to emphasize one of these aspects.

Task 1. In this task, we standardized the authoring process by providing step-by-step instructions for the participants to complete. Specifically, participants are required to locate a specific area on the story piece, generate a new story piece at that location, and further locate a finer area on the new story piece to generate another new story piece, thus connecting to form a story line containing three story pieces. Subsequently, participants need to enter each story piece sequentially, add specified text and images, place data labels and record viewpoints at specified locations, and then exit the story piece. This structured workflow ensures that participants in both the VR and desktop systems have a comparable workload, facilitating a fair comparison between the two environments.

Task 2. In this task, we asked participants to freely create an immersive data story based on a given textual narrative. Specifically, we provided a text story describing arrest or shooting incidents distribution characteristics in New York City. Participants are tasked with authoring a story that conveys the content of this textual narrative. Throughout this task, participants were allowed to freely switch between the inter story piece interface and intra story piece interface, making use of various interactive features.

7.5 Experiment Design

The conducted user study followed a full-factorial within-subjects design. We used a Latin square (two groups) to balance the study conditions (VR and desktop). Each participant was required to complete each task in both authoring systems, resulting in four-story authoring sessions per participant. To mitigate the potential impact of repetition (where participants might become more proficient in authoring the same story in the second session) and to ensure reasonable consistency in the content across authoring sessions, two distinct stories with a similar amount of entities and information but different dataset were created for each task to ensure a consistent difficulty level (*i.e.*, four stories in total for two tasks).

In Task 1, two stories (Story 1 and Story 2) featured the distribution of arrest and shooting incidents between 2007 and 2014, with identical authoring steps for both. In Task 2, two stories (Story 3 and Story 4) featured the distribution of arrest and shooting incidents between 2015 and 2022, with similar content in both stories.

On average the study took around 50 minutes, including familiarization and questionnaire completion. At the beginning of the experiment, participants are allocated 20 minutes to learn and familiarize themselves with both systems, following the same tutorial procedure. Subsequently, participants complete tasks according to the task sequence assigned to them. An independent expert is asked to rate the viewing experience of their VR stories. This is done

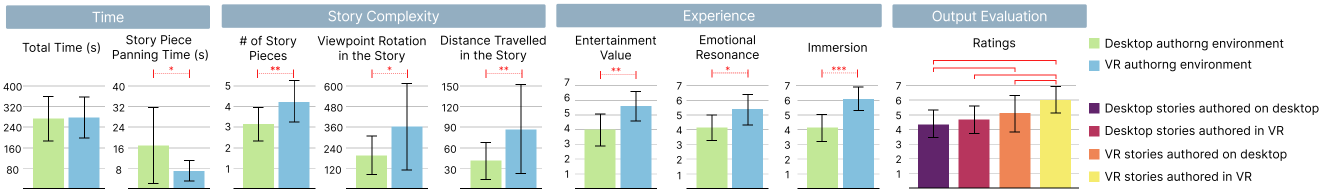


Figure 6: The quantitative measurements and ratings collected from the user study. Significance levels are denoted as follows: (*) for $p < 0.05$, (**) for $p < 0.01$, and (***) for $p < 0.001$. For ratings of the output story, solid lines indicate $p < 0.05$.

to control variables between the environment in which the story is authored and the environment in which it is viewed when evaluating the viewing effects of the generated stories. After completing all tasks, participants fill out a questionnaire used to evaluate the authoring experience and their further feedback will be collected.

7.6 Hypothesis

In our user study, we posit the following hypotheses:

Time. We expect desktop to outperform VR based on previous studies, which found desktop interactions faster than VR interactions due to less required movement [3, 5, 11, 68]. We expect using VR will reduce the time spent on moving story pieces because expansive visual space may reduce the need for rearranging story pieces.

Story Complexity. We expect that participants will create more story pieces in VR due to the expansive visual space. And due to the potentially more convenient and natural viewpoint rotation and translation for participants in the VR environment [47], we expect that stories authored in the VR environment will contain more viewpoint rotations and greater distances of viewpoint movement.

Experience. We expect that the authoring experience in the VR environment will offer better entertainment value, emotional resonance, and immersion due to prior assessments of spatial perception in VR and desktop environments [37].

Output Evaluation. We expect that the ratings of generated stories, ranked from highest to lowest, will be as follows: VR stories created in the VR environment, VR stories created in the desktop environment, desktop stories created in the VR environment, and desktop stories created in the desktop environment. This is because existing research suggests that VR has advantages in immersive storytelling [16] and the consideration of consistency between the authoring environment and the viewing environment.

7.7 Measures

We collected quantitative and qualitative data for each study condition to capture participants' task performance, authoring experience, and output evaluation. Specifically, we used the following measures. **Time:** We measured the total time participants spent on authoring stories in Task 1, and the time spent moving story pieces. **Story Complexity:** We measured the number of story pieces created by participants during authoring in Task 2, the amount of viewpoint rotation performed, and the total distance traveled. **Experience:** Participants were asked to complete a questionnaire rating their subjective experience with different authoring environments after completing all tasks. Considering the general-purpose scale might have limitations in reflecting fine-grained user experience, our rating criteria included entertainment value, emotional resonance, and immersion. **Output Evaluation:** An independent expert was asked to rate the experience of viewing each story authored by participants in both desktop and VR environments. Additionally, **feedback** from participants regarding feelings and thoughts about two authoring environments and their authoring experience, were collected.

7.8 Results

We reported results encompassing quantitative measurements and ratings. Due to the non-normal distribution of most variables, we employed Wilcoxon signed rank tests [71] for statistical analysis. Significance levels are denoted as follows: (*) for $p < 0.05$, (**) for $p < 0.01$, and (***) for $p < 0.001$. Considering the sample size, we reported Cliff's delta (absolute value, denoted as δ) as an effect size indicator, along with statistical power (denoted as $1-\beta$, and $\alpha = 0.05$). The results are illustrated in Fig.6.

Time. We did not find that the authoring environment had an impact on the total time ($p = 0.74, \delta = 0.094, 1-\beta = 0.064$) spent on Task 1, but this may be due to the insufficient sample size and the non-significant result should be interpreted cautiously. We found that in the VR environment, participants spent less time moving story pieces compared to the desktop environment ($p = 0.047, *, \delta = 0.63, 1-\beta = 0.66$).

Story Complexity. We found that in Task 2, participants created more story pieces($p = 0.0036, **, \delta = 1.04, 1-\beta = 0.97$). Stories authored in the VR environment include more viewpoint rotations ($p = 0.016, *, \delta = 1.09, 1-\beta = 0.98$) and greater distances of viewpoint movement ($p = 0.0027, **, \delta = 0.84, 1-\beta = 0.88$).

Experience. Based on participants' ratings of the authoring experience in different environments, we found that storytelling in the VR environment resulted in higher ratings for entertainment value ($p = 0.0018, **, \delta = 1.39, 1-\beta > 0.99$), emotional resonance ($p = 0.012, *, \delta = 1.17, 1-\beta = 0.99$), and immersion ($p = 0.00089, ***, \delta = 1.73, 1-\beta > 0.99$).

Output Evaluation. According to the expert's ratings of the storytelling experience in different authoring and viewing environments, we found that the highest rating of storytelling experience was achieved when viewing VR stories authored in the VR environment. The p-values have been adjusted using the Bonferroni correction to account for multiple comparisons, and the alpha level has been adjusted accordingly in the power calculation. When the authoring environment was the same, the rating of VR stories was higher than desktop stories ($p = 0.021, *, \delta = 0.71, 1-\beta = 0.88$, and $p = 0.00033, ***, \delta = 1.30, 1-\beta > 0.99$). We did not find the authoring environment for desktop stories affect the rating of the stories ($p = 1.0, \delta = 0.34, 1-\beta = 0.20$), but this may be due to the insufficient sample size and the non-significant result should be interpreted cautiously. The rating of VR stories authored in the VR environment was higher than VR stories authored in the desktop environment ($p = 0.0144, *, \delta = 0.79, 1-\beta = 0.94$).

7.9 Key Findings

Based on the experimental results and participant feedback, we summarize and discuss the following key findings.

Less time was spent moving story pieces in VR compared to desktop environment. Our hypothesis, based on prior research [3, 5, 11, 68], suggested that desktop interactions might be faster due to reduced physical movement, but we found fewer interactions, such as moving story pieces, are required in VR. Three participants noted, *"Authoring in a desktop environment requires a lot of time adjusting the size and position of story pieces to avoid obstructions."* This aligns with existing studies [38, 52] that highlight how open spaces in virtual environments enhance observational efficiency.

Stories created in VR were more complex. We observed that VR authoring resulted in more spatiotemporal scenes, as well as movement and rotation of viewpoints. Seven participants reported, *"Moving and rotating the perspective using VR headsets is much easier than using a mouse and keyboard."* These might indicate that the immersive environment can motivate creators, encouraging them to engage more actively in the creative process. For instance, efficient perspective control in VR [47] enhances creators' enthusiasm when designing camera poses.

Stories authored in VR evoked better emotional resonance and engagement. The realism and immersion of virtual environments facilitate deeper emotional experiences. One participant mentioned, *"Seeing bullets appear in front of me in VR leaves a stronger impression than on a screen."* This emotional resonance helps creators convey their insights more effectively to their audience [29]. Moreover, with appropriate viewpoint design, objects in virtual environments can deliver greater visual impact [33].

Stories authored in VR got higher ratings. The expert commented that "overall, stories created in the VR explored more interesting scenes and selected more engaging perspectives." A key reason for the better outcomes in VR authoring is the consistency between the authoring and viewing environments.Three participants noted, *"It's difficult to imagine what the audience will see when creating a VR story in a desktop environment."* The broader field of view in VR compared to desktop settings may promote creators' understanding of the story's impact and their ability to communicate insights effectively to the audience.

8 Discussion

Based on the development and evaluation process, we primarily discussed the following implications and limitations of our work.

8.1 Implications

Expanding the Hierarchical Narrative Framework to Accommodate the Authoring of Stories with More Diverse Structures. Narrative visualization can be categorized into author-driven and reader-driven approaches [62]. Author-driven narratives focus on effectively conveying the creator's insights to the reader, while reader-driven narratives emphasize the reader's active exploration of the story. In our work, we primarily consider the creator's goal of effectively communicating their insights on spatiotemporal data to the audience. Therefore, we propose an author-driven hierarchical narrative framework, resulting in a linear structure that connects scenes and viewpoint transformations in the output story. In non-author-driven story structures, such as the Martini Glass Structure [55], the scenes and viewpoint changes can be organized into a tree-like structure. We noted that the structure formed by the connections between scenes and viewpoints determines the presentation of the story. This insight led us to explore the potential for our hierarchical narrative framework to be adapted to various other story structures: retaining the three-tiered structure of story line, story pieces, and viewpoints while changing the connections between story pieces and viewpoints to accommodate stories with different structures.

Multi-View Layouts of Story Pieces in Virtual Environments. Multi-view layouts, which reveal details at different scales and locations through the presentation of a hierarchical arrangement of multiple views, have been shown to support better performance than traditional explorations on desktop displays [52]. We anticipated that the expansive display area, complemented by natural physical navigation methods such as rotating one's head and moving within the space [**?**], along with embodied interactions like using two hands to perform pinch-to-zoom gestures [73], would positively support complex multi-view layouts. Also, we observed that participants predominantly arranged story pieces in a semicircular-wraparound layout in virtual space. Compared to other arrangement forms, such as flat-wall and circular-wraparound, research [38] indicates that participants overwhelmingly preferred the semicircular-wraparound layout, suggesting it offers a good compromise between the two extremes of display curvature. This insight inspired us to design interactions for adjusting layouts, allowing users to make flexible arrangements. By introducing commonly used multi-view layout patterns, the system can support automatic layout assistance for story pieces. When authoring complex stories, a large number of story pieces can become chaotic, disrupting the creator's logical flow. Automatically generating layouts based on the logical sequence between story pieces may provide an effective solution.

Authoring Data Stories in Mixed Reality. From our experimental results, we found that VR environments have advantages in immersively observing spatiotemporal scenes and selecting viewpoints. However, we also face challenges with VR in terms of text input and precise interactions [60]. Moreover, many established tools related to story authoring (such as image editing and data processing tools) are still limited to desktop environments. Therefore, solely relying on VR environments for authoring data stories has its limitations. To integrate the advantages of immersive and desktop environments, mixed reality may be a promising approach. Researches [44, 46] have demonstrated the significance of mixed reality applications in narrative interaction. Additionally, we have identified the potential of applying mixed reality to data story authoring. By facilitating flexible switching and integration between desktop and immersive environments, tasks can be handled more effectively according to the strengths of each environment.

8.2 Limitations and Future Work

The evaluation results indicate that our proposed hierarchical narrative structure and ST^{2}VR show promise in assisting story creators in authoring expressive spatiotemporal data stories. However, during the system implementation and evaluation processes, we identified several limitations. We hope to highlight these limitations to inform potential future work.

Further Evaluation. We evaluated the system through a usage scenario and a user study. While we believe this evaluation is valid, it could be further strengthened. Our system and the created data stories have not been compared with existing mature story authoring tools or data stories and the number and scope of participants in our user study were limited. Additionally, We can better evaluate our approaches by developing a more comprehensive evaluation framework, combining established general usability scales with immersive storytelling-specific scales.

Enhancing Storytelling Formats. Our work primarily focuses on narrating spatiotemporal data stories through viewpoints movements within spatiotemporal scenes. The viewpoint transition design in our system can be more refined and flexible to enhance the user experience. Also, Improving the current spatiotemporal data real-time processing methods would make our system better suited for larger datasets. Additionally, data stories can also be conveyed through visual combinations [12], fact sheets [70], and data videos [2]. These storytelling formats are currently unsupported by our hierarchical narrative framework and ST^{2}VR.

Strengthening Story Content. The visual elements presented in our system mainly rely on pre-imported data and textual, image, and 3D model assets. Our system lacks the capability for real-time editing of these materials, such as inputting text through voice or gesture [7, 8]. Moreover, visual and auditory effects are crucial for enhancing storytelling in immersive narratives [16, 50]. In our future work, we will further consider supporting larger and more complex spatiotemporal datasets, incorporating features for overlaying and comparing different types of data.

Collaborative Authoring of Data Stories. Collaboration in immersive environments is a promising research direction [53, 61]. Our proposed hierarchical narrative structure breaks stories down from a top-down perspective into relatively independent story pieces, making it structurally suitable for collaborative authoring of data stories. Additionally, our implementation of a desktop counterpart of ST^{2}VR has validated the universality of the hierarchical narrative structure across different environments, allowing for potential collaboration among users in various environments.

9 Conclusions

We have introduced a hierarchical narrative structure for authoring spatiotemporal data stories in immersive environments. By breaking down the authoring process into story line, story pieces, and viewpoints, we aim to help story creators grasp the overall narrative while immersively designing details within the story. Based on our narrative structure, we developed ST^{2}VR, a VR authoring system for spatiotemporal data stories. The system features two types of interactive interfaces to support the organization of story pieces and facilitate immersive design within each story piece. We subsequently evaluated the system through a usage scenario and a user study. The results demonstrate that our approach effectively aids and promotes the authoring process of immersive spatiotemporal data stories.

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