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3DStoryline: immersive visual storytelling

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Abstract In this study, we investigate the potential of immersive environments, such as virtual reality (VR), for enhancing storyline visualizations. Storyline visualization has gained attention as an innovative method for illustrating the progression and dynamics of stories across various domains. However, traditional approaches use 2D lines on 2D screens, which, due to limited space and simplistic layouts, often struggle to effectively represent complex stories involving multiple characters and intricate temporal and spatial dynamics. To address these limitations, we explore the use of immersive VR environments as a storytelling medium. We began by identifying key design considerations for effective storyline visualization in VR. Guided by these considerations, we developed 3DStoryline, a system that allows users to view, navigate and interact with 3D immersive storyline visualizations by exploring storylines from multiple angles and perspectives. To evaluate the effectiveness of 3DStoryline, we conducted a task-based user study, revealing that the system significantly enhances users' comprehension of complex narratives. Through our exploration of storytelling visualization in VR, we recognize the potential of 3D immersive environments in assisting users to better understand complex story structures.

Keywords Virtual reality · Storyline visualization · Interaction design

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1 Introduction

The last decade has seen a concentrated research focus on storyline visualization, an effective visual representation demonstrating the evolution of time-series datasets. Initially, it was used to illustrate a movie narrative, with each character denoted by a single line (Munroe 2009). The character interactions are conveyed by the convergence and the divergence of two corresponding lines at an instant. Typically, one axis encodes time from left to right, and the other encodes a value in these visualizations, aiding viewers in comprehending temporal patterns of entity relationships (Liu et al. 2013). In an attempt to balance comprehensive information presentation, aesthetic appeal, and visualization compactness, researchers have developed various optimization methods for visualization algorithms. Gronemann et al. (2016) computed and leveraged a layout that has the minimum number of line crossings to increase the legibility and aesthetics. Qiang et al. (2017) conveyed a greater amount of story information using hierarchy and sector mapping.

While these methods effectively use simplistic 2D lines to depict entire stories, they face significant limitations when representing complex temporal relationships and narrative elements, especially in stories involving numerous entities. One main reason is the reliance on compact 2D layouts to maintain aesthetic representation. These layouts often minimize white space and aim to keep lines as straight as possible. However, in lengthy and intricate stories, the abundance of lines can lead to visual clutter and obscured elements, making it difficult to follow individual lines and comprehend events. Another limitation lies in the medium itself—storyline visualizations are typically constrained to 2D screens, restricting the layout and spatial arrangement of characters and events. This limited dimensionality hampers the ability to effectively represent complex narrative structures. To address these challenges, previous works have explored alternative design principles and optimization goals, deviating from traditional approaches that prioritize minimizing line wiggles, crossings, and white space. For instance, He and Zhu (2020) proposed a hybrid storyline visualization with spatial information introduced on the y-axis to integrate spatio-temporal information in a single view. Tang et al. (2018) conducted several user studies and interviews, discovering that users preferred utilizing white space and line features to present narratives in hand-drawn storylines. Despite these advancements, these methods remain confined to 2D screens, limiting their ability to fully address the complexity of narrative visualization. This motivates us to explore a broader range of encoding methods and presentation spaces, such as immersive VR environments, to overcome these constraints and enhance the storytelling experience.

In recent years, the rapid development of immersive technologies like virtual/augmented reality (VR/AR) has captured the attention of researchers in the field of visualization. Unlike the traditional monoscopic 2D monitor screen, immersive environments provide stereoscopic rendering and allow users to interact with data visualizations intuitively using 6 DOF (degrees of freedom) input. These technologies offer substantial benefits for the comprehension of data visualizations and task accuracy across various types of datasets, including point clouds (Franzluebbers et al. 2022; Kraus et al. 2020; Zhao et al. 2024), climate data (Helbig et al. 2014), geographic data (Yang et al. 2018) and historical fragment visualizations (Derksen et al. 2023). The immersive and engaging features of VR/AR enable users to focus more effectively on data features and tasks related to domain-specific problems. Furthermore, because they offer significant advantages for storytelling by fostering a sense of immersion and empathy (Hood 2020), immersive technologies are also highly beneficial in education (Doolani et al. 2020) and entertainment (Dal Falco and Vassos 2017), enhancing the user experience in these areas. Based on this understanding, we predict that these immersive environments would also be highly engaging for depicting narrative stories, providing users with a deeper connection to the story elements and the progression of the narrative. However, it remains unclear how to best leverage the advantages of immersive environments in storytelling to maximize their potential.

These questions prompted us to investigate effective storytelling techniques in VR, starting with the traditional storytelling technique—storyline visualization. When considering 3D storylines in VR, many factors need to be addressed. First, we need to consider the layout of the storyline: How to construct a storyline in 3D space so that key features or main characters and story shots are easily noticeable by viewers. Time and location of events are two key aspects of stories. Traditional 2D storylines represent time as a sequence of events presented from left to right. Tang et al. (2020) proposed a mixed-initiative approach to support easy customization of storyline visualizations. Therefore, the spatial location of events can also be considered in storyline designs. Although 3D space is a promising environment for presenting spatio-temporal data, it remains unexplored how to best arrange the characters (who), time (when), locations (where), and events (what) within it. Second, through the workshop of iStoryline (Tang et al. 2018), we observed that people are usually attracted to different aspects of a story, such as main characters, significant events, and sometimes minor or emotional events. When creating storylines, these "important" narrative perspectives often shape the entire visualization. Thus, it would be interesting to explore approaches that utilize the unique features of immersive environments to organize stories for various narrative perspectives. Lastly, one of the key factors that distinguishes immersive storytelling from traditional 2D stories is that users are situated inside the story. This feature allows for many innovative designs. For instance, users can walk around an event or character, and they can interact directly with these narrative elements. Understanding how to best use these unique features to enable users to comprehensively understand narratives is crucial.

In this work, we conducted a preliminary user study to understand how users interpret narratives in VR. We then proposed design considerations for 3D storylines from the following aspects: narrative perspective, visual encodings, layout design, and user interaction. Based on these considerations, we developed 3DStoryline, a novel visualization and interaction tool for immersive storytelling. To evaluate its usability and effectiveness, we conducted a formal user study. The results demonstrated great potential in assisting users to understand complex story structures. In summary, we make the following three main contributions:

- generating design considerations for 3D storyline visualizations in immersive environments;
- proposing 3DStoryline, a novel tool that leverages the immersive capabilities of VR to present complex narratives through 3D storyline visualization; and
- discussing insights and suggestions for future research and development in immersive storytelling techniques, highlighting the potential and challenges of using VR for narrative visualization.

2 Related work

Our research centers on storyline visualization and immersive storytelling. We first reviewed the related work on these two topics. Additionally, our work is highly related to spatio-temporal visualization and incorporates conventions of Space-Time Cube (STC) visualization in the immersive environment. Thus, we review immersive spatial–temporal visualization in the third section.

2.1 Storyline visualization

Since Munroe (2009) introduced hand-drawn narratives for the XKCD comics in 2009, storyline visualization has found extensive applications across various fields. Cui et al. (2011) utilized storyline visualization to help readers understand evolving topics in the narrative. Lu et al. (2014) proposed storyline visualization to demonstrate cooperative relations among the developers in project management. Ren et al. (2023) proposed a novel classification scheme for authoring tools based on narrative perspectives. Storyline visualization is also frequently used to combine geographical information (He and Zhu 2020; Hulstein et al. 2022), integrating geospatial context into storyline visualizations by employing various strategies to composite time and space. Progress in narrative visualization, especially in layout algorithms, has promoted research into automating storyline algorithms. This aims to balance comprehensive information presentation, narrative aesthetics and computational efficiency. Ogawa and Ma (2010) proposed design considerations for line layout from an aesthetic perspective. Liu et al. (2013) developed layout optimization algorithms to efficiently visualize hierarchical relationships among entities over time, enhancing the storyline's aesthetic appeal and making it easier to comprehend and follow. Tanahashi et al. (2015) utilized storyline visualizations for streaming data, enabling users to track and interpret dynamic information effectively. Research and methodologies have also introduced multi-layer storyline visualization techniques (Padia et al. 2018, 2019) to showcase various timelines simultaneously, as well as nested layouts for numerous entities (Pena-Araya et al. 2022).

2.2 Immersive storytelling

Immersive storytelling is a narrative technique that creates interactive and engaging experiences where the audience feels as though they are part of the story via 360-degree video (Eiris et al. 2020; Elmezeny et al. 2018) or head-mounted display devices (Ceuterick and Ingraham 2021). This technique is extensively utilized across diverse fields, including education (Doolani et al. 2020), journalism and communications (Dowling and Miller 2019), medical training (Hardie et al. 2020), and museum exhibitions (Dal Falco and Vassos 2017). The benefits of immersive storytelling have been extensively studied. Immersive environments enhance user immersion and empathy in storytelling (Hood 2020), facilitating a deeper connection with the characters (Chopra et al. 2021; Hollick et al. 2021). Furthermore, interactions within immersive storytelling can significantly boost user engagement (Zhang et al. 2019), which further enhances user motivation (Mystakidis et al. 2014). Natural interactions minimize user distraction, allowing for high-level engagement within the story (Liang et al. 2017). Additionally, interaction can minimize the cognitive load associated with understanding complex narratives. According to narrative theory (Coste 2017), narrative elements, structure, hierarchy, scale, spatial–temporal frame, and context need to be considered in storytelling. Interactive storytelling can help manage them, preventing them from overwhelming the user simultaneously. Despite the benefits of interactive storytelling in immersive environments, there is a noticeable lack of systematic research specifically focused on 3D storyline visualization techniques. This includes aspects such as encoding, layout, and interaction design.

2.3 Immersive spatio-temporal visualization

Exploring spatio-temporal data are a common task in geovisualization field, which is an interdisciplinary field involving geographic information science, cartography and data visualization (Kraak 2006). A frequently adopted visualization technique for spatio-temporal data is the Space-Time Cube (STC), which illustrates the data across spatial and temporal dimensions inside a cubic volume, originally introduced in the 1970s (Ilägcrstrand 1970). Spatio-temporal data visualization is usually leveraged together with a map representation to demonstrate the spatial features (Yang et al. 2019) and is situated above the map with various visual representations such as trajectories (Tominski et al. 2012; Wagner Filho et al. 2019)) and bars (Ready et al. 2018). The horizontal surface is often used to represent geographic spaces, and the vertical direction is encoded by time. In recent years, the rapid development of immersive environments has bolstered research on immersive STC (Ens et al. 2020; Wagner et al. 2024). The inherent 3D feature of the immersive environment greatly amplifies the advantages of STC. Wagner Filho et al. (2019) first introduced STC into the Immersive Analytics domain. Zhang et al. (2022) proposed TimeTables to facilitate data exploration on STC with embodied interactions in virtual reality, demonstrating high usability in spatio-temporal data analysis. 3D hexglyph maps (Horst et al. 2022) is a multi-variable data visualization method that merges STC and Hexbin Map techniques within the VR environment, which is proficient in analyzing complex trajectory match data from notable electronic sports games.

Storyline visualization and STC visualization are both techniques for representing and analyzing spatio-temporal data, but they emphasize different aspects and are used in distinct contexts. STC focuses on the precise representation of spatio-temporal data and is widely applied in contexts that require exact spatio-temporal analysis. In contrast, storyline visualization highlights narrative and character interactions. Although studies in immersive data analysis have examined STC visualization and interaction, there has been a notable lack of research addressing how to visualize narrative stories and organize spatial layouts from a high-level perspective in the immersive environment.

3 Design consideration

3.1 Preliminary user study

To better understand users' perspectives in depicting narratives in VR, we conducted a preliminary user study.

Participants We invited 2 domain experts in the field of visualization from the local university, each with>3 years of professional experience in visual storytelling design and development. In addition, we recruited another 10 unpaid participants (5 male, 5 female), 20–32 years old ($M = 25.6$, $SD = 3.04$), to share their suggestions. Among them, 4 use VR at least once a week, 4 at least once a year, and 2 have never used VR devices. Overall, they owned on average 3.7 years of visualization-related experience and came from different backgrounds, thus helping us to gather insights from multiple aspects.

Task and procedure We began by introducing the basic concept of storyline visualization to the participants. We displayed two 2D storyline visualizations for the movies *Jurassic Park* and *The Moon and*

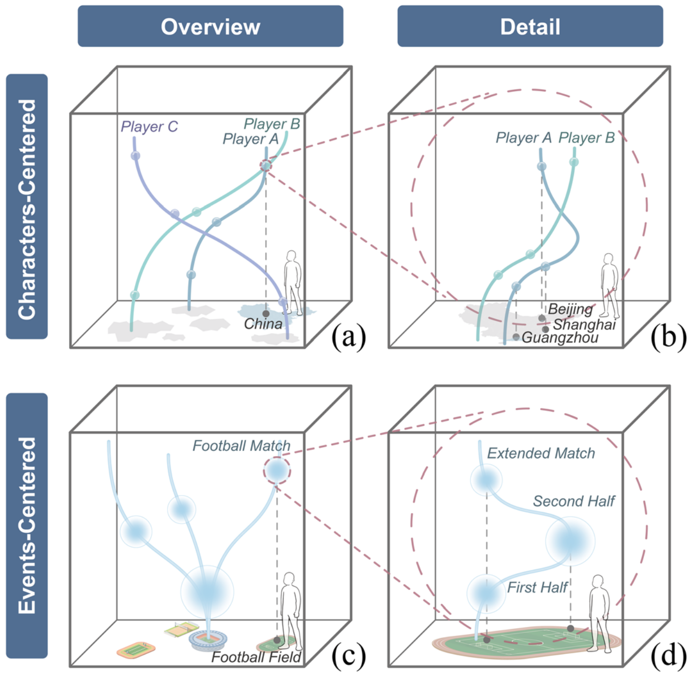

Fig. 1 Narrative perspectives. The vertical upward direction encodes time while the horizontal surface represents the geographical map

Sixpence, using iStoryline (Tang et al. 2018) and StoryFlow (Liu et al. 2013) illustrations. We explained how visual elements were used to represent narrative components. Once participants had a basic understanding of storyline visualizations, we demonstrated a story piece selected from the VR game *Half-Life: Alyx* to show alternative ways to depict stories in VR. We then invited participants to revisit storyline visualizations, this time in VR, and consider the following questions:

- How should these storylines look in VR (layout)?
- What visual elements would best represent events and characters (visual elements)?
- What aspects of the story would they focus on if presented in VR (narrative aspects)?
- How would they want to interact with the visual/narrative elements (interaction)?

Participants were encouraged to share their insights at any time. Afterward, we conducted semi-structured interviews to collect ideas.

Findings Participants mentioned diverse narrative perspectives they would focus on if the storyline were presented in VR. Both domain experts and six participants expressed optimism about following the lines to understand the characters' stories. As one participant noted, "I would like to follow the lines to track where the characters have been through time." while another stated "The lines can indicate the locations of characters and where they would go." Additionally, some participants, including both domain experts and two others, highlighted the advantages of presenting location and chronology of events in VR. For example, one remarked "It was interesting to be in the story in person with the characters. I can stand in a position and view what events have happened there." Another added "It is possible to find what happens at a specific place at a certain time by observing where the lines converge."

From their responses, we noticed that characters and events remain the most important narrative perspectives. This finding aligns with the design of traditional 2D storylines and is consistent with Schell's conceptualization of storytelling, which emphasizes the importance of characters and events (Schell 2008). Participants expressed interest in knowing the characters involved in specific events, the relationships between multiple characters (interaction among characters), and the sequence of events. The layout of the storyline may depend on the narrative perspective.

For conveying this information, line visualizations would still be effective in VR to connect events over time. Points could be used to represent the spatial–temporal position of the character, and spheres could be used to mark key events (similar to closed contours filled with color in 2D storyline (Tanahashi and Ma 2012). The spatial positions on the floor can be well-designed to present locations in the story. Additionally, 4 participants highlighted the importance of focusing on specific events or characters within the context of the story.

3.2 Design considerations

Based on the needs of participants viewing narratives in VR, the congruence of focusing narrative perspectives with traditional methods, and the deliberation of visual elements as previously discussed, we formulate the following design considerations for 3D storyline visualization in VR:

DC1: Narrative perspective Adapt the layout and visual elements based on the narrative perspective. Consider how characters, events, and their relationships are best represented from different narrative perspectives.

DC2: Visual encodings Use line visualizations to connect events over time effectively. Spheres can be employed to mark key events, and various visual elements should be considered to represent characters, events, and their interactions.

DC3: Layout design Arrange the storyline in 3D space to ensure that key features, main characters, and significant events are easily noticeable by viewers. Utilize spatial position to represent different locations in the story.

DC4: User interaction Design interactions that allow users to explore the storyline intuitively. Enable users to walk around events and characters, and interact directly with narrative elements to gain a comprehensive understanding of the story.

4 3DStoryline

We developed *3DStoryline* based on our design considerations. In Sects. 4.1, 4.2 and 4.5, we illustrate how *DC1*, *DC2* and *DC4* lead to specific designs. In Sects. 4.3 and 4.4, we describe the translation of *DC3* in terms of layout design and optimization. In addition, Sect. 4.6 depicts our implementation.

4.1 Narrative perspective

To provide diverse narrative perspectives *(DC1)*, We introduce two approaches: Events-Centered and Characters-Centered (as shown in Fig. 1).

Events-centered perspective This focuses on the story's development, including the sequence of events (temporal), their locations (spatial), and the correlations between them. Relevant events are connected to indicate their time sequence and relationships, helping readers develop a comprehensive understanding of the story's progression.

Characters-centered perspective This allows users to follow specific characters, including the events they experience, changes in their locations, and their relationships. In addition, the preliminary study revealed that users are interested in both the overall story and specific events. Therefore, we support users in obtaining both an "overview" of the story and "detail" of particular events.

Overview The entire story, including the time sequence, events, locations, characters and their interactions, is presented. This allows readers to gain a comprehensive understanding of all events and characters.

Detail A specific event is presented clearly, showing the location, time and characters involved in that event. Note that, this "detail" searching can be based on location ("what happened here"), time ("what happened at that time"), or character ("what happened to this person"). This allows readers to view both the "overview" and "detail" from both the "Events-Centered" and the "Characters-Centered" perspectives.

4.2 Visual encodings

Following *DC2*, we use 3D points, bounding spheres, and connecting lines to depict story developments in VR.

3D points A 3D point represents the location (at different scales) of a character, visualized only in the *Characters-Centered* design. When the detail view is enabled, more points show detailed locations the character visited. For example, in the overview (Fig. 1a), a 3D point can represent a football player having matches in China. When zooming in, more points appear (Fig. 1b), showing matches in Shanghai, Beijing, and Guangzhou.

Bounding spheres A bounding sphere indicates an event (at different scales), appearing only in the *Events-Centered* design. When the detail view is enabled, more bounding spheres show sub-events. For instance, in the overview (Fig. 1c), a bounding sphere represents a football match. When zooming in (Fig. 1d), more details such as the goals in the first half, second half, and extended match will appear as distinct bounding spheres. The size of the sphere (radius) indicates the event's importance to the entire story.

Lines Lines connect points or bounding spheres, indicating the traveling path of characters or the sequence/correlation of events.

Color Color is used to differentiate characters in *Characters-Centered* design (Fig. 1a and b).

4.3 Storyline visualization

We leveraged the immersive Space-Time convention (Ens et al. 2020; Wagner et al. 2024; Zhang et al. 2022), where the vertical upward direction encodes time and the horizontal plane represents 2D geographic information. Meanwhile, we visualized the spatio-temporal narrative data by the Characters-Centered and Events-Centered Perspectives proposed in Sect. 4.1.

Characters-centered perspective The concept of 3D points mentioned in Sect. 4.2 refers to the character c's spatial–temporal coordinate extracted from data entries in the original dataset. For a character c, we obtained a list of spatial–temporal 3D points from the original dataset as $\mathbf{r}^c = \{\mathbf{r}^{c_0}, \mathbf{r}^{c_1} \ldots \mathbf{r}^{c_n}\}$, in which $(\mathbf{r}_x^{c_i}, \mathbf{r}_z^{c_i})$ represents the 2D geo-location and $\mathbf{r}_y^{c_i}$ is the time of the ith 3D point $\mathbf{r}^{c_i}$. Each 3D point $\mathbf{r}^{c_i}$ has an impact factor ξ_c^i, which dictates whether $\mathbf{r}^{c_i}$ should be visualized in the overview or Detail. when ξ_c^i is larger than a pre-defined global threshold ξ_c^{thre}, $\mathbf{r}^{c_i}$ is visualized in overview by tiny transparent balls with unique size (Fig. 1a). Vice versa for detail, if $\xi_c^i \leq \xi_c^{\text{thre}}$, $\mathbf{r}^{c_i}$ is visualized in detail (Fig. 1b). Next, in both overview and Detail, we link the 3D points by time sequence for each character with lines in different colors by cubic spline interpolation. To be noted, the 3D points visualizations and the character lines are only visualized in the Characters-Centered Perspective. In the Events-Centered Perspective, it is hidden.

Events-centered perspective We collect all the events $\mathbf{e} = \{e_0, e_1 \ldots e_m\}$ from the dataset. For the jth event e_j, it has attributes including (1) the start time t_{start}^j, (2) the end time t_{end}^j, (3) the spatio-temporal coordinate $\mathbf{r}^{e_j}$, where $(\mathbf{r}_x^{e_j}, \mathbf{r}_z^{e_j})$ is the 2D geo-location where it happens and $\mathbf{r}_y^{e_j} = \frac{t_{\text{start}}^j + t_{\text{end}}^j}{2}$, and (4) event impact factor ξ_e^j, which is quantified by how long the event lasts in our design. when ξ_e^j is larger than a pre-defined global threshold ξ_e^{thre}, $\mathbf{r}^{e_j}$ is visualized in overview by the opaque bounding sphere with the radius equal to ξ_e^j (Fig. 1c). Vice versa for detail, if $\xi_e^j \leq \xi_e^{\text{thre}}$, $\mathbf{r}^{e_j}$ is visualized in detail (Fig. 1d). Then, we connect the center of the bounding spheres based on the sequence of the events with lines by the cubic spline interpolation. Be noted that the event visualization and event lines only exist in the Events-Centered Perspective.

4.4 Layout optimization

To better support *DC3*, we develop the layout optimization methods for storyline visualization along the time axis, as well as for 2D geo-map.

Storyline layout along time axis The narrative often spans extensive time scales and is distributed nonlinearly along time axis, which can lead to widespread distribution or overlapping of visual elements. To prevent space wastage and visual clutter, we propose a nonlinear mapping method that expands dense regions and compresses sparse ones. This is achieved by rearranging 3D points and bounding spheres along the time axis in three steps, ensuring a pre-defined distance between all the bounding spheres. This layout optimization is applied separately to both the overview and Detail views.

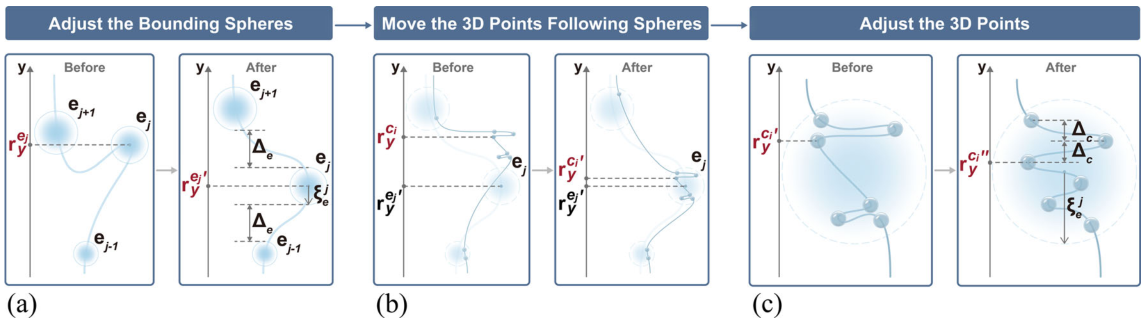

Fig. 2 Method for optimizing storyline layout along the time axis involves three steps: **a** adjusting the coordinates of bounding spheres to ensure a consistent distance Δ_e between them, **b** updating the positions of 3D points within each bounding sphere, and **c** fine-tuning the 3D points inside each sphere to maintain a uniform distance Δ_c between them

First, we recalculate the coordinates along the time axis of each bounding sphere. For *j*th bounding sphere, we calculate the new time coordinate $\mathbf{r}_y^{e_j}{}'$, ensuring that the distance along the time axis between the boundary of event sphere e_j and the neighbor event sphere e_{j+1} is Δ_e (Fig. 2a), denoted by:

$$\mathbf{r}_y^{e_{j+1}}{}' - \mathbf{r}_y^{e_j}{}' = \Delta_e + \xi_e^{j+1} + \xi_e^j, j \in [0, m-1] \tag{1}$$

We pre-define the time coordinate of 0th sphere $\mathbf{r}_y^{e_0}{}'$. We then derive $\mathbf{r}_y^{e_j}{}'$ from Eq. 1 as:

$$\mathbf{r}_y^{e_j}{}' = \mathbf{r}_y^{e_0}{}' + \sum_{\tau=0}^{j-1}(\Delta_e + \xi_e^\tau + \xi_e^{\tau+1}), j \in [1, m] \tag{2}$$

Second, we move all the 3D points inside the bounding spheres to the new positions, following the movement of the bounding spheres (Fig. 2b). For a given 3D point $\mathbf{r}^{c_i}$, if

$$\exists j \in m, |\mathbf{r}^{c_i} - \mathbf{r}^{e_j}| \le \xi_e^j \tag{3}$$

we say the character c is involved in the event e^j at 3D point $\mathbf{r}^{c_i}$ at moment $\mathbf{r}_y^{c_i}$ with geo-location $(\mathbf{r}_x^{c_i}, \mathbf{r}_z^{c_i})$. We denote this relationship by $\mathbf{r}^{c_i} \in e^j$. Then we move the 3D point $\mathbf{r}^{c_i}$ to the new coordinate $\mathbf{r}^{c_i}{}'$ based on the movement of e^j's bounding sphere:

$$\mathbf{r}_y^{c_i}{}' = \mathbf{r}_y^{c_i} + (\mathbf{r}_y^{e_j}{}' - \mathbf{r}_y^{e_j}) \tag{4}$$

Third, we rearrange the 3D points inside the event sphere to a sequential layout (Brehmer et al. 2017) (Fig. 2c) with a uniform distance Δ_c between $\mathbf{r}_y^{c_i}{}'$ and $\mathbf{r}_y^{c_{i+1}}{}'$ along the time axis, where Δ_c is defined by:

$$\Delta_c = \frac{2\xi_e^j}{N} \tag{5}$$

For a given bounding sphere of event e^j, if a 3D point $\mathbf{r}^{c_i}{}' \in e^j$, we update it's time coordinate to $\mathbf{r}^{c_i}{}''$ by:

$$\mathbf{r}_y^{c_i}{}'' = \mathbf{r}_y^{e_j}{}' + (INDEX - \frac{N}{2}) * \Delta_c \tag{6}$$

where N is the number of 3D points enclosed by sphere of event e^j and *INDEX* is 3D point $\mathbf{r}^{c_i}{}'$'s index among all the enclosed 3D points. By following three steps, we achieved a uniform layout along the time axis (Fig. 3).

Geo-map layout Typically, a narrative story encompasses a variety of scenarios. Characters interact with each other in different scenarios. Events in different scenarios are correlated. In our design, each scenario is visualized via 2D geographical maps in the immersive environment. In detail view, the geo-map of a specific scenario is visualized in Cartesian Coordinates (Fig. 4b). In the overview, multiple geo-maps of the scenario are integrated, allowing the user to gain a comprehensive view of the story. We utilize a polar coordinate system centered on the user's position to determine the location of each map (ρ, θ) (Fig. 4a). To maintain awareness of key characters and events, maps of higher importance are visualized with a smaller ρ. The importance of a map is calculated by integrating the impact factor of each event and the 3D point

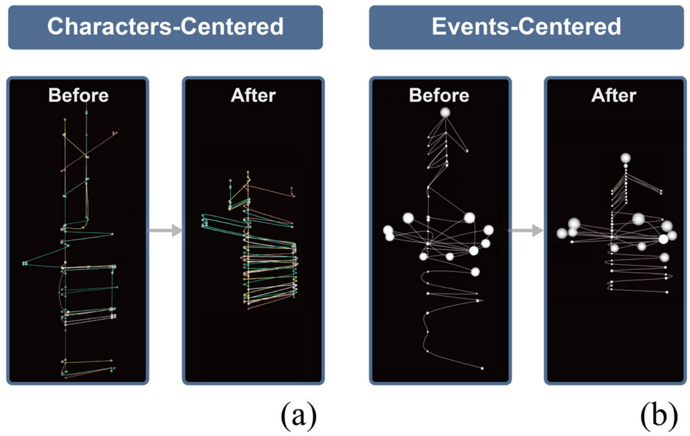

Fig. 3 Storyline layout along time axis: **a** Characters-centered perspective and **b** Events-centered perspective

associated with it. The parameter θ for each map is calculated using force-directed methods to achieve an optimal layout. Please note that the layout of the maps in the overview is generated only once, based on the user's initial location when the program starts. It does not update as the user navigates through the immersive environment.

4.5 User interaction

To meet *DC4*, we develop the following interaction techniques to support users in exploring the stories.

Switching Specifically, users can use two pre-defined buttons on the VR controller to switch between the Characters-Centered and Events-Centered Perspectives, as well as between the overview and Detail views. When changing perspectives, the visualization of the current perspective gradually fades out while the visualization of the target perspective gradually emerges. When switching from overview to Detail, the user will enter the map nearest to their current location.

Navigation On the one hand, users can either teleport or walk around on the geo-map (ground) within the immersive environment. On the other hand, they can control the storyline, moving it up and down along the time axis, using the sticker/pad on the VR controller.

Storyline exploration When the user touches the 3D point, event sphere, or the character/event line, basic information (e.g., name, geographic information, time) will be displayed. In addition, we support users in viewing the Characters-Centered Perspective view locally enclosing in the bounding sphere of an event by selecting the corresponding bounding sphere. This helps users to explore the correlation between characters and a specific event.

4.6 Implementation

we developed 3DStoryline with Unity3D (as shown in Fig. 5). We leveraged an all-in-one VR head-mounted display Meta Quest 2 (1832 × 1920 resolution per eye, 100° FOV, 90Hz refresh rate). It was streamed on a PC (Intel Core™ i7 2.21GHz, 32GB RAM, GeForce RTX 3070, 24GB video memory). 3DStoryline allows users to load datasets in XLSX or CSV format containing names of characters and events, time-space information, sequence/correlation of events, impact factors of characters and events, and additional attributes displayed in the interaction.

5 Evaluation

5.1 Design

Similar to iStoryline (Tang et al. 2018) and PlotThread (Tang et al. 2020), rather than focusing solely on the accuracy of storyline visualizations, our emphasis is on evaluating users' experience and assessing our design from a narrative perspective. This includes the design of visual encodings, layout, and user

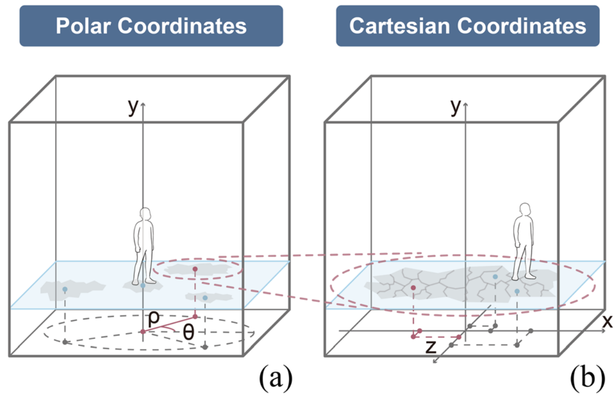

Fig. 4 Geo-map layout: **a** Overview and **b** Detail

interactions when perceiving 3D storylines in a VR environment. To achieve this, we gathered users' quantitative feedback, observed their behaviors, and conducted interviews to understand their experience. Additionally, we aimed to explore how quickly participants could locate information, such as specific story events, characters, and relationships, within the storyline visualization. Therefore, task completion times were recorded.

5.2 Dataset and tasks

We created a narrative dataset derived from the TV episode story *Loki*, featuring multiple characters traveling across time and various universes. The dataset contains 411 character and 95 event records, with attributes such as start and end times, the importance of characters or events. The dataset is open-source and available at github.com/NarrativeDataset/NarrativeDataset_LokiEpisode1. In the study, we defined four tasks, each with unique scenarios from the story:

- *Task1* Finding specific story scenes to check if our tool supports navigating to different detailed scenarios of the story.
- *Task2* Pointing out specific events or characters to demonstrate the validity of visual encodings for events and characters.
- *Task3* Identifying a set of events or characters in a specific relationship to evaluate the tool's ability to show relationships between characters or events in detailed narratives.
- *Task4* Determining the key event in the story that caused a change in a specific character's relationship to show how our tool helps in understanding the story overview.

5.3 Participants

We recruited 12 unpaid participants (7 males and 5 females) from the local university, all right-handed, aged 18–28 years old ($Mean = 24$, $SD = 3.20$). All participants majored in computer-related fields, with 10 having a Bachelor's degree or higher. This ensured participants were skilled in using electronic devices to facilitate users' focus on using the system to explore the narratives. Eight participants have previous experience with 2D storytelling systems, to gain potential insights about converting from 2D to 3D. All participants had a normal or corrected-to-normal vision and could distinguish the colors required by our application. None were familiar with the dataset or the TV episode *Loki*.

5.4 Procedure

Before the study began, we surveyed participants about their familiarity with the TV episode *Loki*. We then introduced the design of 3DStoryline, explaining the narrative perspective, visual encodings, layout, and interaction techniques. Participants were provided with an example story scenario to explore using our tool until they were comfortable with its design. Afterward, we gave them a brief summary of the *Loki* story and

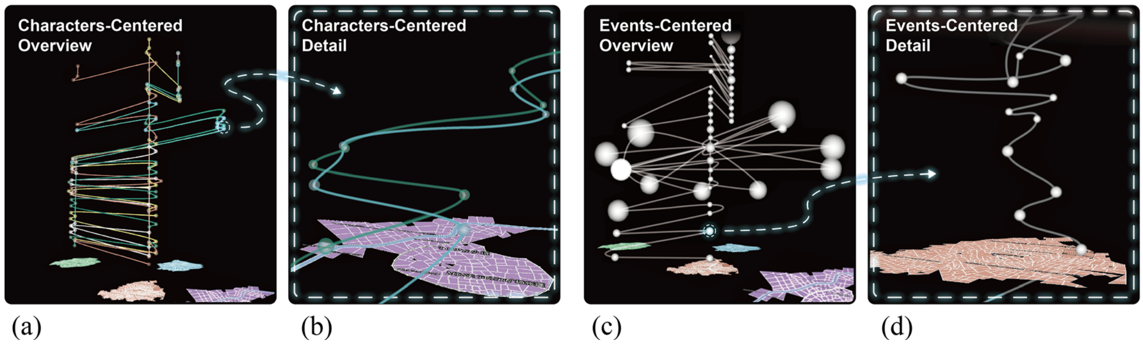

Fig. 5 Storyline visualization of the TV episode story *Loki* in VR environment. Users can switch between narrative perspectives to focus on either a Characters-centered or Events-centered perspective: **a** Characters-centered perspective in overview, **b** Characters-centered erspective in detail, **c** Events-centered perspective in overview, and **d** Events-centered perspective in detail

showed a short video about the background and main characters. Then, participants were asked to perform the four tasks in a fixed order.

After each task, participants completed an After-Scenario Questionnaire (ASQ) with 7-point Likert scales. At the end of the study, they completed a System Usability Scale (SUS) questionnaire with 5-point Likert scales, a Presence (PQ) Questionnaire with 7-point Likert scales, and a User Experience Questionnaire (UEQ) with 7-point Likert scales. A semi-structured interview followed to gather additional feedback on tool effectiveness and user experience. Each session lasted approximately one hour. The quantitative data from questionnaires were calculated and reported as means and 95% confidence intervals. Qualitative feedback and behavior observations were organized and classified for presentation.

5.5 Quantitative results

ASQ results The ASQ measured satisfaction with ease, time, and supporting information for each task shown in Fig. 6a. In *Task1*, satisfaction with the ease ($M = 6.167$, $CI = [5.757, 6.667]$), time ($M= 6.167$, $CI = [5.757, 6.667]$), and supporting information ($M = 6.0$, $CI = [5.275, 6.81]$) had high ratings. In *Task2*, satisfaction with the ease ($M = 6.167$, $CI = [5.757, 6.667]$) and time ($M = 6.25$, $CI = [6.005, 6.58]$) received high ratings, while supporting information ($M = 5.667$, $CI = [4.797, 6.622]$) was slightly lower. In *Task3*, satisfaction with the ease ($M= 5.917$, $CI = [5.537, 6.387]$), time ($M = 6.583$, $CI = [6.303, 6.958]$), and supporting information ($M = 5.417$, $CI = [4.432, 6.492]$) showed a similar trend. In *Task4*, high ratings were achieved for ease ($M = 5.75$, $CI = [5.07, 6.515]$), time ($M = 6.0$, $CI = [5.38, 6.705]$), and supporting information ($M = 6.333$, $CI = [5.823, 6.928]$). Overall, participants were highly satisfied with the ease and time required to use the system to explore narratives. However, satisfaction with supporting information in *Task2* and *Task3* was relatively low, with slightly higher rating uncertainty.

SUS results The left chart in Fig. 6b shows the participants' SUS final scores for our system. According to Bangor's adjective rating scale (Bangor et al. 2009), the mean of SUS scores ($M = 85.0$) was near the excellent range, and the confidence interval ($CI = [79.916, 91.499]$) is above the good score, indicating that the system was acceptable. And the sample standard deviation ($SD = 9.108$) is reasonable.

PQ results The middle chart in Fig. 6c illustrates the PQ ratings, divided into involvement, naturalness, resolution, and interface quality, applicable to assessing presence in immersive environments for use. The involvement ($M = 5.462$, $CI = [5.082, 5.932]$), naturalness ($M = 5.667$, $CI = [5.427, 5.997]$), and resolution ($M = 6.125$, $CI = [5.675, 6.660]$) received high ratings, while interface quality ($M = 4.917$, $CI = [4.232, 5.692]$) was relatively low. Overall, participants had a good sense of presence when completing tasks using our system, but the interface quality slightly negatively impacted their experience.

UEQ results The right chart in Fig. 6d illustrates the UEQ ratings, which contain six aspects: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty, for assessing overall user experience. Attractiveness ($M = 6.363$, $CI = [6.138, 6.678]$), dependability ($M = 6.104$, $CI = [5.794, 6.504]$), stimulation ($M = 6.271$, $CI = [5.941, 6.686]$), and novelty ($M = 6.333$, $CI = [5.973, 6.788]$) had high scores. However, perspicuity ($M = 5.660$, $CI = [5.365, 6.040]$) and efficiency ($M = 5.563$, $CI = [5.213, 6.002]$) were relatively low. Overall, our system demonstrated good dependability and novelty, and was found to be

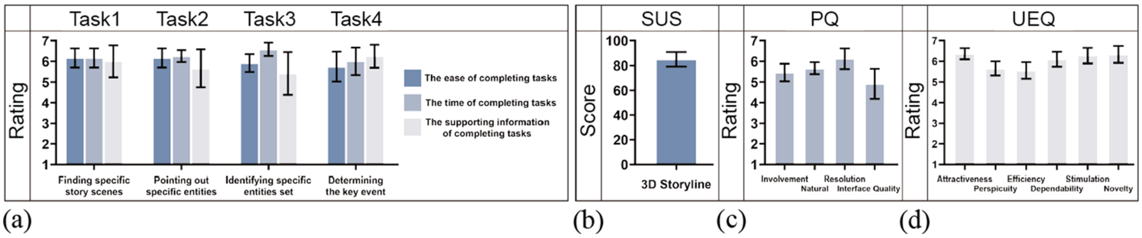

Fig. 6 Geometric mean scores of **a**, **b** ASQ, **b** SUS, **c** PQ, and **d** UEQ. Error bars show 95% confidence intervals

attractive and stimulating to participants. However, there is potential for improvement in perspicuity and efficiency.

5.6 Qualitative feedback

Narrative perspective All participants easily understood the rationale behind the two narrative perspective designs, *Events-centered* and *Characters-centered*. To answer the questions, they could switch between these perspectives easily to view the story from different angles. Additionally, they used both the *Overview* and *Detail* views to explore the broader context or obtain more specific information.

Regarding the time spent on the two perspective views, we noticed that most participants (10 out of 12) frequently toggled between them, searching for answers from both character and event perspectives. Two participants primarily used the *Characters-centered* view, switching to the *Events-centered* view only for event-related tasks. They mentioned enjoying the focus on characters as it helped them deeply understand character changes and imagine how these characters influenced the story's development. They noted that traditional storytelling techniques do not allow such a focus on specific characters.

Additionally, the flexibility of switching between *Overview* and *Detail* was highly appreciated. Participants (5 $\times$) mentioned that both the context and details are equally important for understanding a story. The simple switches between *Overview* and *Detail* and between *Events-centered* and *Characters-centered* perspectives significantly supported their ability to quickly comprehend the story background, details, and character relationships.

Visual encodings Visual encodings were easy to understand in the study. Participants noted that they could easily track location changes in the Characters-centered storylines. The size of the bounding sphere helped them identify important events. The multi-scale design supported their understanding of the overall story trend and the characters' travel paths while allowing them to focus on the details of significant events and actors. Although color was used only to indicate different actors in the study, participants suggested it could be an effective visual cue for indicating additional story information, such as enemies or opponents, character status, or relationships, depending on the story's content.

Layout design The spatial–temporal layout provided a 3D view of location and event timelines. Participants were impressed by the ability to "stand" inside the story. This situated visualization helped them understand location, time, events, and actors in various ways. For example, they could focus on a specific city on the map to see which characters visited and when, or what events happened there and in what order. Participants could also follow the *Events-centered* storyline to grasp the story's progression. One participant stated, "The map and the storylines support me in better understanding the relationship between characters along the temporal dimension and the correlation between the events and the geographic information." Another participant commented, "Standing in the position of the storyline of the actor, I can feel more about what he was experiencing." These findings indicate that 3DStoryline and the spatial–temporal layout effectively support users in understanding "what happened here," "what happened at that time," and "what happened to this person."

User interaction In the study, participants quickly understood and remembered the interaction methods. All participants agreed that these methods were easy and effective for detecting story pieces and navigating through the story. However, our main focus was on the storyline visualization in the 3D space, so the interaction methods provided were limited. Participants suggested many innovative interaction designs. For instance, they recommended including a transition when switching between narrative perspectives to better relate the context of the event to the characters involved.

6 Discussion

In this section, we discuss our insights into designing 3D storytelling techniques and presenting storyline visualizations in immersive environments. We also address the limitations of our work and provide suggestions for future developments in immersive storytelling techniques.

6.1 3D storytelling techniques

Storytelling techniques have been extensively discussed in previous research (Ren et al. 2023). Stories can be narratives (Mitchell and Egudo 2003), movies (Glebas 2012), or data-driven stories (Stolper et al. 2018) that convey messages such as findings, insights, or trends through data. These data are collected and visualized to form story pieces, which are then connected in meaningful order to support the original story message. Thus, a story does not need to be limited to 2D. If the data are 3D spatial data or multiple dimensions are required to support the story message, a 3D story may be more effective.

This work focuses on one particular storytelling technique—storyline visualization, which uses lines to represent characters, events, and their relationships. Although we have not compared 3D storylines with 2D ones regarding user preference and story comprehension, we have already seen their potential. Compared with a 2D layout, 3D storylines involve an additional dimension to present information. This raises the question of what this extra dimension adds to storytelling. In this work, we explored the combination of geographical visualization and storyline visualization, situating the storylines based on location of events and characters. Building on this, we organized the stories from two perspectives: *Events-centered* and *Characters-centered*. Together, the design effectively presents the key factors of stories: who, where, when and what. This approach offers users a more comprehensive understanding of the story. However, there are many other alternatives for 3D storyline visualizations. For instance, we could combine network visualization with storylines to not only show relationships between individuals over time but also allow us to observe how these relationships change through time.

However, compared to 2D layouts, many design decisions need to be made for 3D storylines. In 2D storylines, data such as changes in individual locations over time are mapped to line curves, trends, and positions, which can be accurately observed on a 2D interface. In contrast, 3D layouts allow users to perceive data from different angles, which can lead to misunderstandings or even ignoring the line curves and the events they represent. Therefore, explicit visual cues indicating the positions of location changes or events become essential. For example, in our work, we use 3D points and bounding spheres to highlight these changes, ensuring that participants can easily notice this information when looking at the 3D storylines. Therefore, we found that participants were satisfied with the ease and time required to use our tool to explore narratives.

Moreover, we need to consider the layout and positions of multiple characters and events (lines with 3D points or bounding spheres). Our goal is to ensure that the arrangements of these visual elements are meaningful without being too dense or too sparse, maintaining both aesthetics and clarity. However, this distribution is influenced by the time and location distribution of the story pieces or events, as well as the narrative perspectives. In our work, the positions of the storylines are determined by the actual locations of events and characters over time. We carefully designed the spatial distribution of points and bounding spheres along the time axis.

6.2 Storytelling in immersive environments

Virtual reality and augmented reality provide immersive experiences that help users understand visualization data (Dwyer et al. 2018). In such environments, users feel as if they are inside the data feature. Moreover, if multiple users are involved, they feel as though they are experiencing the data together. In this work, we explored users' experiences of viewing not just simple data or scenes, but meaningful story visualizations. Here, we share our insights on visual storytelling in immersive environments.

When designing storytelling techniques for immersive environments, we need to consider how best to utilize the advantage of its features to enable users to comprehensively understand narratives. For instance, VR environment can significantly enhance users' engagement in the story (Mills 2021). In this work, we make use of 3D space to present the spatial–temporal feature of narratives. We allowed users to observe narratives from two narrative perspectives: *Events-centered* and *Characters-centered*. Users are fully immersed in the storylines and engaged in exploring events and characters with different interaction methods, including *Overview* and *Detail*, and navigation. The study results indicated that participants had a strong sense of presence. They reported enjoying the feeling of standing inside the story and experiencing events from the actor's perspective. Therefore, we suggest future research can consider using large-scale visualization and situated visualization for immersive storytelling. Immersing users in the narrative and visual elements in VR can effectively engage them in the story.

Through our exploration, we also noticed that interaction techniques are crucial for exploring stories in VR, especially when offering various narrative perspectives. Participants frequently switched between *Events-centered* and *Characters-centered* perspectives (mode changing). They usually observed the story's overview to understand the overall trend, then walked (navigation) to regions of interest (ROI), such as an event or actor, and zoomed in to check more details (overview and detail). Although not yet implemented in the current system, we imagine that users would be interested in using their bodies to interact with narrative elements. For instance, crouching to check more details related to a location, gazing to show more details of the focused element, or grabbing lines together to rearrange the storylines. In addition, multimodal interactions, including gestures, voice commands, and even haptic feedback, could provide a richer and more engaging experience. These interactions allow users to engage with the story in a more natural and intuitive manner, enhancing their immersion and understanding.

6.3 Limitations and future work

In this work, we explored the possibility of transcending traditional storyline visualization approaches by utilizing 3D structures to depict narratives. Furthermore, we investigated the potential of VR environment in narrative storytelling. In this section, we discuss the limitations of our work and lessons learned. We hope that our efforts will inspire more in-depth research into immersive storytelling.

First, we provide two narrative perspectives (events and characters) and two view modes (overview and detail) in the system. To comprehensively understand relevant storylines and viewpoints, users can switch between these perspectives and view modes. However, users may get confused about these two perspectives during narrative exploration. For instance, a user focusing on detailed information about an important event may want to check the actors involved. They can switch from the *Events-centered* view to the *Characters-centered* view. In the *Events-centered* view, bounding sphere explicitly indicated individual events. After switching to the *Characters-centered* view, the bounding sphere disappears, and involved actors' traveling paths during the event appear. Since the visual designs in both perspectives are similar (points, bounding spheres, and connecting lines), users may get confused about which perspective is enabled. Therefore, future work should extensively consider all perspectives, the visual element designs, and the transitions between them.

Second, the interaction methods provided in the system are limited. Future work can explore multimodal interactions to support users in exploring and creating stories, such as gestures, gaze, and voice commands. User studies could be further conducted to evaluate the usability and effectiveness of these interaction techniques in the immersive environment. Additionally, the VR environment holds promise for storytelling to a group of audiences, enabling shared experiences and collaborative exploration of narratives. However, many design decisions need to be considered in collaborative storytelling. For instance, what visual content should be shared with all audiences and how they can share their insights. This includes determining the best ways to display shared information, facilitating communication between users, and ensuring that the interactive elements are accessible and engaging for everyone involved.

Third, we have not yet compared 3D storyline visualizations with traditional 2D designs. The advantages of 2D designs have been extensively explored in previous research, showing that users can comprehend the development of entire stories at a glance. Line features have been effectively mapped to the relationship or characteristics of the actors. On the other hand, we have also noticed the advantages of 3D storylines, which can integrate more information, more perspectives and embed more features in the lines. Future work can further compare these two representation approaches to evaluate their effectiveness, usability, and impact on user comprehension and engagement.

Last but not least, our work focuses on a specific storytelling approach—storyline visualization. However, many other storytelling approaches exist, such as animation, simulation, and more flexible interactive systems. Additionally, our work deals specifically with narrative data. Future research can explore the effects of other storytelling forms across different types of stories.

7 Conclusion

In this work, we explored approaches for presenting abstract storyline visualization in VR environments. We discussed our design considerations and demonstrated a system of 3DStoryline visualization. We further evaluated its usability and discussed our findings and insights through this research. What we want to share at the end of this study is that immersive storytelling holds great potential for sharing and communicating insights. When creating such systems, designers should be very clear about the data type, the message of the stories, and the story pieces that can be used to support the message. These elements shape the story and determine the environment that would best host such stories.

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