GeoAnimation: A Grammar for Animated Geographic Visualization

Jie Yu*
School of Software Technology
Zhejiang University

Zhenning Chen†
State Key Lab of CAD&CG
Zhejiang University

Di Weng‡
School of Software Technology
Zhejiang University

Yingcai Wu§
State Key Lab of CAD&CG
Zhejiang University

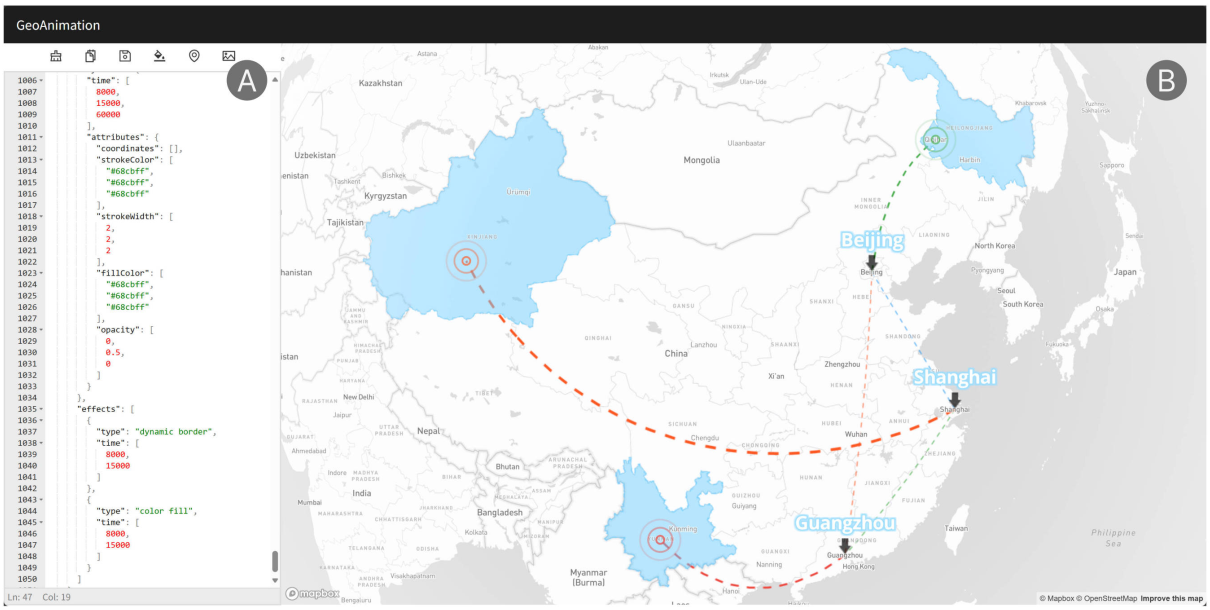

Figure 1: The GeoAnimation system consists of two main views. Editing View (A) provides declarative syntax editing and rich interactive functions. Visual View (B) provides view functionality. Each time the json syntax is updated in View A, it will be updated synchronously in View B.

Abstract

In recent years, animated geographical visualization has arisen as an intuitive narrative medium for presenting and disseminating geographic information, with extensive applications across various domains. However, existing approaches to creating geographic animations often face trade-offs among learning curve, ease of use, the complexity of output videos and other limitations. To further lower the barrier for producing geographic animations, we first conducted a survey of 50 geographic data animations and synthesized a design space that outlines the key elements in geographic animation presentation. Based on this, we designed a declarative grammar targeted at geographic animations. Then we developed an interactive tool called GeoAnimation to enable animators to create geographic animations efficiently and effectively. Finally, we verified the usefulness of our tool through two use cases and expert interviews conducted with two experts. The results indicate that GeoAnimation enables animators to quickly and conveniently create satisfactory geographic animations, effectively reducing the barriers, tedium, and inconvenience associated with creating such animations.

Index Terms: Geographic Animation, Animation Creation, Geographic Visualization, Grammar

*E-mail: jieyuu@zju.edu.cn.
†E-mail: czn@zju.edu.cn.
‡E-mail: dweng@zju.edu.cn. Di Weng is the corresponding author.
§E-mail: ycwu@zju.edu.cn.

1 Introduction

Geographic animation is a media form that dynamically visualizes geospatial information and data [30, 27]. As a crucial component of narrative visualization [23, 47, 41], it seamlessly integrates geographic information, visualization techniques, and storytelling skills [30, 41, 47]. This integration has led to its extensive application across diverse fields, including weather forecasting, traffic simulation, and urban planning. Characterized by vividness, intuitiveness, and accessibility, these animations have emerged as a highly effective medium for expressing and disseminating geographic information. They are now commonly featured on major social media platforms and professional websites, such as YouTube.

However, creating geographic animations is not an easy task. Existing tools such as Canis [16] and CAST [15] have achieved significant advancements in the field of animation. Canis provides a declarative language to standardize data-driven chart animations, while CAST further builds upon this foundation by offering an interactive tool that enables non-programming users to easily create chart animations. Meanwhile, Animated Vega-Lite [50] advances the integration of animation with interactive graphics by unifying animations with an interactive graphics grammar.These contributions have laid important foundations for animation techniques. Nevertheless, when it comes to geographic animations, these general-purpose tools exhibit certain limitations. For example, they are not specifically designed for geographic visualization and often fail to fully support particular geographic elements. This limitation restricts the richness and expressiveness of geographic animation creation. Thus, animators often use video production software such as Adobe After Effects [22] to manually process videos of geographic visualizations. Although video production software offers a high level of flexibility and intuitiveness during the animation creation process, it lacks specialized capabilities for analyzing geographic data. Users are required to manually integrate and animate geographic elements. This manual approach is not only time - consuming and labor - intensive but also increases the likelihood of errors and inconsistencies.

The limitations above have motivated us to explore an interactive approach that enables animators to create desired geographic animations more efficiently and conveniently. In this study, our aim is to design a grammar specifically for geographic animations, which can assist animators in creating geographic animations more conveniently and effectively. Nevertheless, achieving this goal faces the following two challenges.

Classification of Geographic Visualizations. A large number of geographic animations involve a variety of visualizations, which necessitates a systematic survey and summary. However, the details of these visualizations are distributed across videos, requiring scientific methods and significant time and effort to capture, record, and organize, which is a challenging task. Additionally, The diverse types of visualizations further complicate this process.

Lack of Intuitive and Effective Tools. Designing an effective tool for geographic animation grammar poses another challenge. Such a tool must provide an intuitive grammar-editing environment to help users iteratively write grammar rules, and generate and observe geographic visualization effects. The design must simultaneously consider the structure of the grammar and the goal of creating geographic animations, ensuring it truly facilitates users in producing animations efficiently.

To address the first challenge, we conducted an in-depth analysis of 50 geographic data animations, extracted key design elements and technologies, and then constructed a design space for geographic data animations, providing rich visualization options and narrative strategies for animation creation. Based on it, we designed a declarative grammar targeted at geographic animations. Then, in order to address the second challenge, we developed an interactive tool, which can quickly animate geographic data by configulating some specialized categorical elements of geography and using time series as the core. At the same time, it supports real-time preview and adjustment functions to ensure that the final animation effect can accurately meet the user's expectations. We named the grammar and tool we designed GeoAnimation.

In order to validate the usefulness of GeoAnimation, we presented two use cases and conducted expert interviews with two professionals in the field. Two use cases show that GeoAnimation supports users to easily create various forms of ideal geographic animations. Expert interviews confirmed the rationality of the grammar we designed and the usability and practicality of GeoAnimation.

The main contributions of this study are as follows:

- A design space that outlines the key elements of geographic animation display.
- A declarative grammar and an interactive tool we designed that simplifies the process of making geographic animations.
- Evaluation including use cases and expert interviews that demonstrates the usefulness of GeoAnimation.

2 RELATED WORK

In this section, we review the recent studies that are relevant to our work, including geographic visualization and storytelling as well as visualization animation grammar.

2.1 Geographic Visualization and Storytelling

Geographic visualization and storytelling are key methods for conveying geographic information and promoting knowledge discovery, especially when dealing with complex geographic datasets [41, 19, 12, 31, 31]. Effective geographic visualization not only needs to present spatial data precisely, but also tell the stories behind the data in an engaging way, thereby stimulating the interest and understanding of the audience [8, 41].

Initially, geographic visualization primarily concentrated on static map design and optimization, including map symbol selection, color coordination, and information layering [45, 46, 43, 4]. Subsequently, with the progress in computer technology, interactive geographic visualization [6] emerged as a new paradigm. The design priority of interactive geographic visualization systems centers on creating user-friendly interfaces and interaction models, aiming to empower users to explore geographic data more efficiently and uncover the underlying patterns and relationships within the data [11, 42, 17, 48]. For instance, enabling interactive functionalities such as zooming, filtering, and selection allows users to independently investigate geospatial information based on their individual interests and requirements [7].

In recent years, the role of storytelling in geographic visualization has received increasing attention [9, 14]. Studies show that through carefully designed narrative structures, visualization can convey information more effectively and evoke users' resonance [36]. Research on data-driven videos further bridges cinematic techniques with visualization, such as analyzing narrative structures through cinematography lenses [2] and studying transition design in data stories [39]. Some researchers have begun to explore how to integrate animation into geographic visualization to enhance its narrative ability. For instance, Thony et al. [41] explored the methods of storytelling in interactive 3D geographic visualization systems. There are also studies focusing on the application of animation in narrative visualization [47, 40].

Camera movement plays an important role in story narration. By analyzing geographic data videos, the design space of camera movement can be summarized, thereby making better use of camera movement to tell stories [49, 29]. For example, GeoCamera [25] achieves exploratory analysis of geospatial data through camera path animation. The existing research on geographic visualization and story-telling has laid a solid foundation for the effective utilization of geographic data for information transmission. Beyond camera techniques, recent tools like DataClips [3] automate data video authoring by binding visual assets to data queries, while AutoClips [35] generates videos directly from data facts, demonstrating the trend toward lowering production barriers. However, how to lower the threshold for creating geographic animations and enable more users to easily create high-quality geographic animations remains an unsolved problem [41, 19].

The goal of GeoAnimation is to lower the threshold for creating geographic animation, enabling more people to use geographic animation for data visualization and storytelling. GeoAnimation aims to provide a flexible and user-friendly interactive approach for geographic animation, enhancing the capabilities of geographic data visualization and narrative.

2.2 Visualization Animation Grammar

Grammar is a series of rules used to define the structure of the formal language [1, 28]. It stipulates which sequences of symbols are the legal expressions of the language. Grammar usually includes a vocabulary or a set of symbols and a set of production rules, which describe how to combine these symbols into larger structures, such as statements or programs [44]. It plays a central role in formal languages and provides the basis for syntax and semantics [26]. Grammar focuses on the structure and form of language, while semantics focuses on the meaning of language. A well-defined grammar can ensure that the syntactic structure of a language is clear, thereby contributing to an accurate understanding of its semantic content [32, 33].

Animation serves as a foundational technique in data visualization, enabling the dynamic representation of temporal and spatial patterns while offering unique opportunities for storytelling, though it also presents challenges such as cognitive overload and implementation complexity [13]. Building on this foundation, Animation Grammar is a formal language used to describe and generate animations [21, 5, 34]. It decomposes animations into a series of basic elements and operations, and creates complex animation effects by combining these elements and operations [37]. A good animation grammar should be able to express complex animation logic concisely and clearly, while providing sufficient flexibility and customizability [24, 10]. Recent advancements in this field include tools like Datamator, which facilitates the creation of datamations through data query decomposition, further lowering the barrier for animation authoring [18].

Early studies on animation grammar mainly focused on general-purpose animation descriptions, such as KeyFrame [38] and animated transitions in statistical graphics [20]. With the continuous development of the visualization field, researchers have begun to explore animation syntax for specific types of data. For example, regarding the animation of statistical graphs, researchers proposed the Gemini grammar [24]. The Gemini syntax describes the animated transitions between statistical graphs by defining transition steps and provides a recommendation system to help users select the appropriate animation effects. Animated Vega-Lite [50] regards animations as time-varying data queries and unifies them with the static and interactive visual abstractions of Vega-Lite.

Different from the above works, GeoAnimation has designed a declarative syntax specifically for geographic animation. This grammar centers on time and geographical transformation, supporting rich geographical elements and animation effects. The grammar design of GeoAnimation fully considers the characteristics of geographic data and the requirements of geographic animation, aiming to provide users with a flexible and easy-to-use way to create geographic animation.

3 Design Space

This section details the process of identifying animation design patterns in geographic animation. Section 3.1 elaborates on the process of our data collection and data analysis, and Section 3.2 elaborates on the design space we have summarized.

3.1 Data Collection

To gain a deeper understanding of the design patterns and best practices of geographic animation, we conducted diverse investigations and collected and analyzed geographic animations, aiming to provide guidance for the declarative grammar development of geographic animation. Our methodology encompasses the following steps: First, we gather a high quality corpus of geographic animations from online sources; Second, we split the video into key clips; Third, we analyze these clips to formulate an design space.

Corpus Construction. To ensure the relevance and quality of the content, we started with a well-known YouTube channel famous for its high-quality geographical animation videos. We selected videos with a minimum of 100 views. From this channel, we analyzed 50 geographic data animations. Then, we expanded our collection based on relevant recommendations and also included web animations. These cases cover multiple themes such as climate change and urban development, fully integrating dynamic map technology with animation design elements, and achieving the visual expression of geographical animation through graphical narrative means.

Video Segmentation. During the processing of video content, we sorted out and processed the original materials, focusing on the identification of key features of geographic visualization content and the precise extraction of effective segments. The video is edited into short clips of no more than 10 seconds. Each valid segment contains at least one geographic information element to ensure the value of geographic data representation. Repeated animations of the same type of elements are also segmented and processed.

Statistics and Analysis. After completing the segmentation and extraction of video clips, we further carried out statistical analysis on these geographical animation clips. The statistical results reveal that in geographical animation, attributes such as location, size, color and transparency are the most common dimensions of change. The changes of these visual attributes constitute the main visual representations of geographical animation. In addition, we have conducted a systematic classification and statistics of the animation effects. Based on the geometric features of geographical elements, the effects are divided into different categories such as points, lines, and regions. The detailed information of these classifications will be elaborated in depth in Section 3.2.

3.2 Result

Here we present a detailed description of the design space we have summarized. The design space is composed of two core dimensions: geospatial targets and visual animation effects. These two dimensions interact with each other and jointly determine how animation effectively conveys geographical information. The animation effect formed by the combination of the two dimensions is shown in Figure 2.

3.2.1 Geospatial targets

The geospatial target serves as the core of geographic animation, specifying the geographic entity or phenomenon to be depicted. Based on the geometric characteristics and data representation needs of geographic entities, we categorize geospatial targets into three fundamental types: point, line, and region targets. Point targets are represented as discrete points on a map, symbolizing specific geographical locations or event occurrence points. They are the smallest visual units but often carry crucial information, such as city locations, monitoring point coordinates, or emergency sites. Due to their simplicity, point targets can quickly draw the audience's attention and become focal points for information delivery in animations. Line targets are depicted as linear geometric shapes on a map and typically indicate connections or paths between geographical entities. They play a role in connecting and guiding in geographic data animations. Examples include transportation routes, river flow directions, population migration paths, or data transmission lines. The animation effects of line targets can effectively showcase the dynamic changes and trends of geographical phenomena, such as traffic flow increases or decreases, river water level variations, or the direction and speed of population migration. Region targets, represented as regional geometric shapes on a map, cover broader geographical regions than point targets. They represent geographical regions with specific attributes or characteristics, such as administrative divisions, ecological zones, urban boundaries, or climate regions. The animation effects of region targets can reveal data distribution within the region, changing trends, and interrelationships among regions.

3.2.2 Visual animation effect

In geographic animations, the effect of visual elements is a key means of expression, and the expressiveness and appeal of geographic information are enhanced by adjusting visual attributes. From the perspective of visual perception, we have summarized the types of point, line and region targets affected by different visual attributes. These effects can be adjusted through parameters to meet the requirements of different geospatial targets and animations.

Position-related effect. For point targets, tailing can simulate the motion trajectory of an object, such as the direction of population movement in a city over a period of time; Path Tracking records

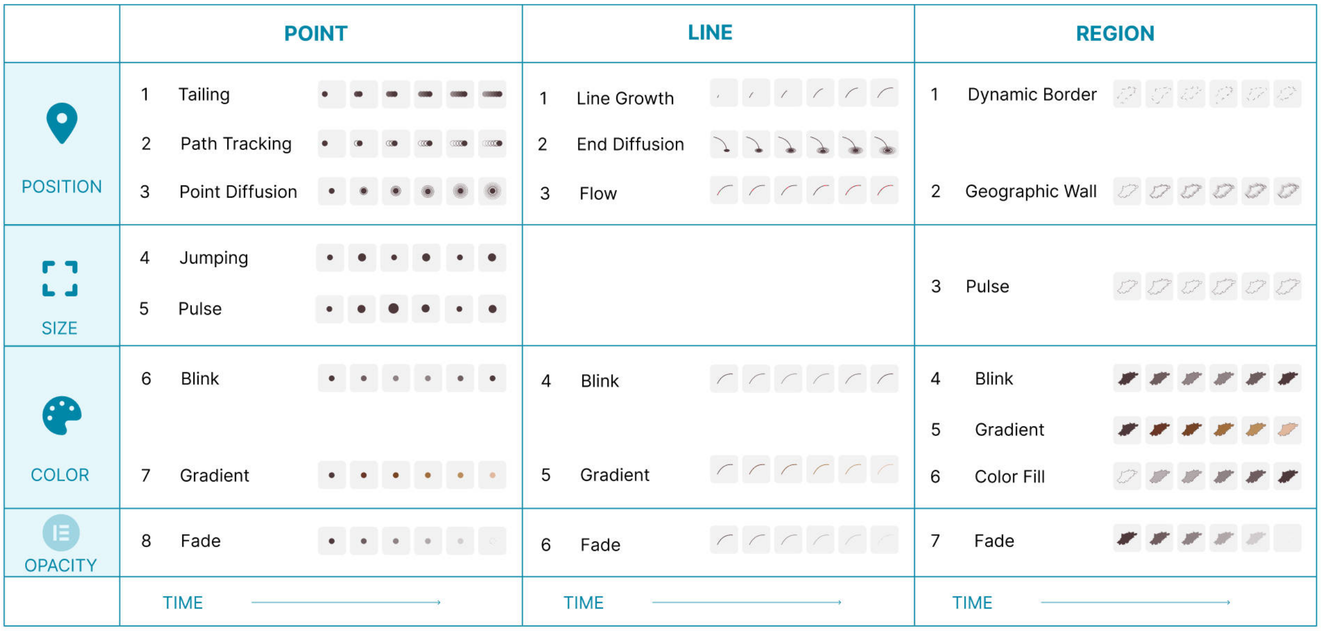

Figure 2: Our design space for the animation effects related to the basic attributes of point, line and region elements in geographic animation.

the changing paths of point targets over time and is suitable for presenting the data trends of monitoring points. The Point Diffusion effect presents the diffusion of phenomena through point diffusion, such as the process of infectious disease transmission. Line targets have the effect of Line Growth and can be gradually drawn to display the progress of transportation line construction or the formation process of rivers. End Diffusion begins to diffuse from the end of the line, highlighting the extension direction of the line and the importance of the end. The Flow effect simulates the flow of line data, such as the flow velocity of a river or the current intensity of a power line. In terms of the region target, the Dynamic Border effect highlights the regional scope through the dynamic changes of the border and can be used to emphasize the boundaries of administrative divisions or ecological regions. The Geographic Wall effect builds a virtual wall to isolate and highlight specific regions, which is suitable for showcasing protected regions or restricting the boundaries of development zones.

Size-related effect. The Jumping effect of the point target makes the size of the point change rhythmically, which can attract the audience's attention to a specific point, such as flashing warning lights; The Pulse effect shows data fluctuations by periodically magnifying and shrinking points, such as the rise and fall of the stock market. It can also be used for region targets. Periodically magnifying and shrinking regions emphasize data changes, such as showing the trend of urban population density changes.

Color-related effect. The Blink effect can be applied to point, line and region targets, rapidly changing colors to attract the audience's attention, and is used to prompt important information or warning signals. The Gradient effect shows the trend of data change through smooth color transitions, such as temperature distribution maps or pollution concentration maps; The Color Fill effect clearly defines the regional attributes or categories of region targets, such as distinguishing different land use types or political regions.

Transparency-related effect. Point, line and region targets can all adopt the Fade effect. By changing the transparency, visual elements can fade in and out, making the animation more natural and continuous when the scene transitions or data changes. For example, when presenting geographic data at different time periods, a smooth transition can be achieved through the fade effect to avoid confusion among the audience due to sudden changes.

Visual animation effects are of vital importance in geographic animation. They can not only enhance the expressiveness of geographic information but also attract the audience's attention through dynamic changes, making complex geographic data more intuitive and understandable. Reasonable selection and combination of these effects can effectively present the geospatial target, meet the various demands of geographic data animation in terms of information transmission, trend display, visual appeal, etc., and bring the audience a vivid and intuitive geographic data visualization experience.

To ensure the relevance and quality of the content, we started with a well-known YouTube channel famous for its high-quality geographical animation videos. We selected videos with a minimum of 100 views. From this channel, we analyzed 50 geographic data animations. Then, we expanded our collection based on relevant recommendations and also included web animations. These cases cover multiple themes such as climate change and urban development, fully integrating dynamic map technology with animation design elements, and achieving the visual expression of geographical animation through graphical narrative means. Through systematic analysis, we have summarized a design space that outlines the key elements of geographic animation display, providing a solid foundation for the subsequent development of our declarative grammar.

4 GEOANIMATION

Based on the design space we constructed and relevant literature review, we have meticulously designed a declarative grammar specifically for geographic animations, enabling both animators and ordinary users to create animations efficiently and conveniently; this grammar incorporates key elements from our design space to provide an intuitive framework for structured animation definition, while our developed interactive tool demonstrates its practical capabilities.

4.1 Declarative Grammar

To design a user-friendly and effective declarative grammar, we first established the following two design goals.

G1: Utilize time series to enhance the narrative of geographic data visualization. Time is a crucial element in geographical animation. It enables the animation to dynamically display the changes of geographical phenomena over time, thereby revealing patterns that may not be obvious in static visualization. By emphasizing the time dimension, users can create more narrative geographical animations to guide the audience in understanding the evolution process of geographical data. For example, users can set the total duration of the animation and precisely control the appearance, behavior and disappearance of each geographical element on the timeline. This behavior coincides with the keyframe concept in design software, which can ensure that different geographical elements are coordinated in time, thereby maintaining the coherence of the visual narrative.

G2: Provide concise and easy-to-use grammar. Considering that many users may not have professional geographic information systems or programming skills, we have designed a JSON-based declarative syntax to enable users to define geographic animations in a structured and intuitive way. This grammar is not only easy to understand, but also enables users to focus on the content and behavior of the animation without having to deal with complex programming details. The animation definition in JSON format enables users to intuitively control the temporal and visual attributes of each geographical element, thereby effectively expressing geospatial goals and dynamic effects.

Based on the above goals, the grammar design focuses on the intuitive correspondence of time and space attributes, and the most important part is shown in the Figure 3. The most crucial design among them is the introduction of the keyframe mechanism - users only need to mark the occurrence, change and disappearance time points of elements in the JSON structure, which can replace complex time programming. This approach significantly lowers the threshold for time arrangement, enabling non-professional users to define dynamic logic through a simple structure as well.

Time control is divided into two levels to achieve collaborative management. First, unify the animation duration through the global "`duration`" field to ensure the synchronous advancement of multi-element animations; Secondly, set the "`time`" field within each element to support time control accurate to the millisecond. For example, a fixed-point element can be set to start moving at 300ms, while a line element can start drawing after a delay of 500ms. Through time misalignment, an ordered visual effect can be formed.

Declarative syntax adopts a hierarchical JSON structure design: the top layer defines the overall parameters, and the bottom layer "`elements`" array accommodates specific geographical elements. Each geographical object (point/line/region) has an independent timeline and spatial attributes. This structure not only adapts to the characteristics of different geographical elements, but also can achieve complex animations through the combination of simple configurations. For example, if an animation sequence of appearing at 0ms, flashing for 500ms, and then moving for 1000ms is set for a point element, a composite animation effect can be automatically generated.

The design of directly associating time parameters with visual attributes simplifies the dynamic expression. The region fill color can be bound to time and automatically gradually change color to represent temperature changes over time. The line width parameter can be associated with time to achieve line growth animation. Users do not need to write time calculation code. They can build data-driven dynamic narratives merely through attribute configuration.

This design refers to the timeline concept of professional animation software, providing precise control while maintaining the simplicity of grammar. Through keyframe arrangement, users can plan the appearance rhythm of geographical elements just like editing a video timeline. When the timelines of multiple elements interact in the global coordinate system, the originally abstract time pattern is transformed into an intuitive visual rhythm. This design strikes a balance between geographical narrative coherence (G1) and grammatical ease of use (G2), enabling users without programming experience to create professional-level geographical animations through visual thinking. Ultimately, through the natural mapping of spatio-temporal attributes, the complex geographical spatio-temporal processes are transformed into editable and disseminable dynamic stories.

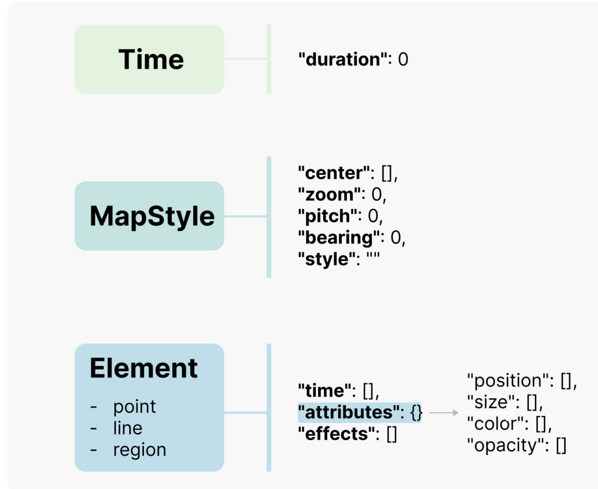

Figure 3: The design framework of the system grammar, time, mapstyle, and element, are three parallel major items. The last two have sub-elements, as shown on the right.

4.2 System

The system adopts a dual-view layout. On the left is the JSON editing view, and on the right is the map display view, as shown in Figure 1. This design provides an intuitive interactive user experience, enabling users to easily create and perfect geographic animations.

In the left view, users can directly input and modify the JSON code that defines the animation. The system also includes a verification function, which can check errors in the JSON code in real time and promptly feed back to the user. This helps users quickly identify and correct any problems, ensuring the smooth creation of the animation. To facilitate users' creation of json, the system also supports the insertion of colors, location coordinates, and images. For instance, location coordinates can be interacted with by clicking, and can be linked with the map view on the right to obtain geographical longitude and latitude.

The view on the right is a dynamic map display, which shows geographical animations. It allows users to interact with the map, such as panning, zooming and rotating, to explore different angles of the animation. The map view also supports multiple visualization layers, enabling users to cover different geographical elements and enhance the richness of the animation.

The synchronization between the two views is a key feature of this system. When the user changes the JSON code in the left view, the system will immediately process the update and reflect it in the map display on the right. This real-time synchronization enables users to immediately see the effects of their modifications and provides immediate visual feedback. This interaction process can help users better understand the relationship between JSON code and the generated animations, thereby making it easier to achieve the expected visual effects.

To enhance usability, the system also includes a set of default templates and examples that users can load and modify. These templates cover common geographic animation scenes, such as point movement, line drawing and region highlighting. Users can start with these templates and customize them according to their specific needs, thereby reducing the learning curve and creating complex animations more quickly.

Overall, the dual-view design of the GeoAnimation system, combined with its intuitive JSON editing function and real-time synchronization of visualization tools, creates a comprehensive environment for users to design and improve geographic animations. By abstracting potential complexities and providing a user-friendly interface, this system enables ordinary users to create engaging and information-rich geographic animations without the need for expertise in geographic information systems or advanced programming skills.

5 Evaluation

Within this section, to showcase how GeoAnimation can realize geographic animation via our grammar, we've developed two sample cases. Through sample cases, we confirmed GeoAnimation's capability in achieving visual effects. Additionally, we conducted an expert interview to assess the usefulness of GeoAnimation.

5.1 Use Cases

To verify the universality of the geographical animation design space, we select two types of typical geographical data visualization scenarios as practical cases. The first case focuses on the multi-scale data presentation in a 2D environment, combining the dynamic interaction between points and facial targets. The second case explores the interrelated expression of complex geographical elements in the 3D space and strengthens the data narrative logic through innovative animation effects.

5.1.1 Case I: Geographical visualization of the China-India air route

In this case, the user attempts to create a video using GeoAnimation to showcase the geographical relationship between China and India, as well as their transportation challenges. This case reproduces partial clips of a video[1] from YouTube.

At the beginning of the video, the user gradually carry out the creation of exclusive videos in accordance with the templates provided by the system. In the initial stage, to ingeniously introduce the theme, the user created two new points, marking the locations of China and India on the map respectively, and precisely determined their geographical coordinates with the help of the system to ensure that these two points accurately correspond to the locations of the countries. Subsequently, the user creates a new line, firmly connecting the two points of China and India, forming an intuitive geographical connection and initially establishing the basic framework of the two countries on the map. Immediately after that, to create suspense and a transitional effect, the user reduced the opacity of the aforementioned point and line, making the picture appear blurred, thereby introducing the latest issue focus - Mount Everest at the border between China and India.

To vividly present this geographical challenge in the video, the user carefully inserted a dot picture and precisely placed it at the position corresponding to Mount Everest on the map. By adjusting the size parameter of the picture, it can be gradually enlarged to attract the audience's attention. Meanwhile, gradually showing numbers are placed beside the picture to quantify the height of the mountain peak, vividly expressing the grandeur of Mount Everest and the great difficulty of crossing it. The dynamic border effect endows this region with agility and a sense of focus, as if constantly reminding the audience of the importance and controversy of this region. The color filling clearly demarcates China's territorial sovereignty over this part, strengthening the sense of boundaries.

[1] Available at https://www.youtube.com/watch?v=KuWAdYl5icY

After completing the presentation of geographical barriers, the user shifted their focus to the in-depth presentation of flight route issues. First, mark out the three key regions of New Delhi in India, as well as Shanghai and Hong Kong in China respectively. Build three new lines to connect them with each other and construct potential flight routes. To enhance the visual expressiveness and dynamic sense, the user added growth effects to these lines, as if the shipping routes were gradually spreading and extending on the map.

Finally, the user focused on the relatively reasonable transfer route from New Delhi to Hong Kong and then to Shanghai, carefully adding the image effect of the aircraft to make this route appear more intuitive and feasible in the video.

Through the four-step progressive visualization presentation of GeoAnimation, the progressive steps are shown in the figure 4. The user has created a geographical animation behind the China-India flight route, highlighting the helpless situation where direct flights between China and India are blocked, and fully demonstrating the complex situation of flight problems between China and India.

5.1.2 Case II: The dynamic interconnection of transportation networks among cities in China

In this case, the user uses GeoAnimation to illustrate China's busy transportation network, with a focus on the connectivity of three major cities: Beijing, Shanghai and Guangzhou. This video is a dynamic display of domestic tourism and logistics.

At the beginning, the user produced video introductions using the system's templates. They located three points representing Beijing, Shanghai and Guangzhou on the map. By leveraging the coordinate assistance of the system, these points are precisely placed to ensure geographical accuracy. To immediately attract the audience, these points have been added with a blink effect, symbolizing their importance as major transportation hubs.

Subsequently, the user established the connections between each pair of cities by drawing lines between them: Beijing - Shanghai, Beijing - Guangzhou and Shanghai - Guangzhou. Incorporate the route growth effect to simulate the gradual development and expansion of transportation routes. The flow effect further enhances the visual representation of continuous movement along these routes.

To enhance dynamics and realism, the user had introduced mobile elements such as freight and passenger trains. These elements cross the route with tails, visually representing the continuous flow of goods and people between cities, as shown in Figure5 (A).

The story develops as the surrounding regions of each city are introduced. The effects of dynamic border and color fill are applied to these regions, emphasizing their influence and the vitality of their traffic networks.

With the development of videos, the user had expanded their transportation networks beyond the original three cities. The new railway line starts from Beijing, Shanghai and Guangzhou and extends to other regions such as Heilongjiang, Xinjiang and Yunnan. These routes are accompanied by the end diffusion effect, as shown in Figure5 (C), symbolizing the expansion scope and influence of China's transportation infrastructure.

Throughout the video, the user adopted a multi-stage visualization strategy. Starting from a single city, expanding to intercity connections, and finally presenting the national network, the animation effectively conveys the complexity and efficiency of the domestic transportation system in China. The use of different colors, widths and dynamic effects not only enhances the visual appeal, but also distinguishes different routes and regions, providing a comprehensive overview of China's traffic landscape.

5.2 Expert Interview

To comprehensively evaluate the effectiveness and usefulness of the GeoAnimation tool, we conducted expert interviews. Below,

Figure 4: Visualization of the geographical issues of the China-India air route: (A) The point and line between China and India. (B) The numbers representing the peaks of the Himalayas that appear after the disappearance of A and the heights of the peaks that change with position. (C) point and line representing New Delhi that do not have direct access to Shanghai. (D) The flight from New Delhi to Shanghai via Hong Kong has added the flight representation on line.

we first introduce the participants and procedures of the interviews, then summarize the expert feedback.

5.2.1 Participants and Procedure

We invited two experts in the field of data visualization to participate in interviews. Both experts possess profound knowledge and understanding of geographic data and geographic visualization, as well as hands-on experience in geographic animation production.

During the interview process, we first provided the experts with a brief introduction to the research background and methodology. We then demonstrated two use cases before inviting them to personally use the GeoAnimation tool to complete a series of specified geographic animation tasks. These tasks included creating animations for point, line, and polygon features, as well as implementing dynamic displays of time-series data. Finally, we conducted semi-structured interviews to engage in in-depth discussions on aspects such as the tool's usability experience, functional evaluation, and improvement suggestions.

5.2.2 Feedback

We have collected the feedback and evaluations from the experts and summarized them as follows.

Ease of learning and use. The experts unanimously praised the learnability and ease of use of GeoAnimation. They stated that they could master the basic operations of GeoAnimation in a short period and successfully create expressive geographic animations. Furthermore, GeoAnimation's declarative grammar and intuitive user interface significantly reduced the threshold for creating geographic animations, making it a tool suitable for both beginners and professionals. Specifically, experts point out that the JSON editor and real-time preview function of GeoAnimation make the animation production process simple and straightforward. Even non-professional users can quickly get started through the templates and verification functions provided by the system.

Effectiveness. Experts provided positive and constructive evaluations of GeoAnimation's effectiveness. First, they spoke highly of the implementation effects of the two cases. For instance, the first case demonstrated a high degree of reproducibility. The experts noted that the video production outcomes were quite impressive, illustrating that GeoAnimation can generate geographic videos with a certain level of complexity and sophistication, which are sufficient to meet most common video production needs in daily life. Additionally, the experts highlighted that the system supports a rich array of geographic elements and animation effects, capable of satisfying the production requirements for geographic animations across different scenarios. Notably, the time-channel and geographic transformation functions offer abundant possibilities for dynamic expression in animations. The experts believe that these advantages are closely tied to the comprehensiveness of our design space and the rationality of the grammar structure, which together provide an important and solid foundation for the effectiveness of our system in producing geographic animations.

Suggestions. Experts have also provided suggestions for improvement. First, experts note that our designed grammar has scalability and could expand its support to include advanced visualization forms such as heat maps, flow maps, and 3D maps. This expansion would enhance the system's versatility and utility. Besides, when handling large-scale data, the system's rendering performance could be further improved for smoother operation. In addition, some experts suggested integrating AI technology into GeoAnimation to automatically generate and recommend geographical stories, thereby improving creation efficiency and offering users innovative experiences.

6 Discussion

This section discusses the implications, lessons learned, limitations, and future work of our study.

6.1 Implications

Our work carries the following implications. First, GeoAnimation lowers the barrier to geographic animation creation. Traditional approaches either have a steep learning curve or involve cumber-

Figure 5: The dynamic interconnection of transportation networks among cities in China: (A) Tail effect. (B) Region color fill effect. (C) End diffusion effect.

some and complex production workflows. The design space we have summarized and the declarative grammar we have designed are specifically tailored for geographic animations, thereby streamlining the animation creation process. This enables even non-expert users to quickly master the tool and generate satisfying geographic animations. This has the potential to democratize geographic animation creation, allowing a broader range of people to participate in geographic data visualization and storytelling. Second, the design space we proposed offers a systematic framework and essential guidance for creating geographic animations. This design space decomposes and analyzes common geographic animation effects from existing animations, providing structured perspectives and methodologies for geographic animation production. It also aids animation creators in developing a deeper understanding of various visual effects and narrative strategies—moving beyond superficial animation design to a more intentional, analytical approach.

6.2 Lessons Learned

In this study, we derived several key lessons. First, during the construction of the design space, the lengthy nature of some videos and the subtlety of certain effects made it easy for us to overlook or confuse similar effects. Through practical experience, we found that slowing down playback or viewing key video segments frame-by-frame helped us avoid such omissions or mix-ups. Second, our initial grammar design adopted a configuration-style approach, where data and effects were scattered across different elements—this meant that adding or modifying requirements necessitated separate adjustments to each component. In contrast, the current grammar aligns better with users' narrative logic, offering greater flexibility and convenience. These experiences underscore that grammar design is rarely a one-time endeavor; it requires iterative refinement and reflection from the user's perspective to achieve excellence. Third, through this entire study, we realized that system design is not necessarily better when it is more complex or feature-rich. Our interactive tool has a simple interface and relatively straightforward functions, yet it effectively assists animators in creating animations with ease. This experience reinforces our belief in the principle of "simplicity is ultimate sophistication"—that even modest, user-centric designs can deliver meaningful value when they align with practical needs. We have come to appreciate the beauty of simplicity and the importance of focusing on core functionalities that truly matter to users.

6.3 Limitations and Future Work

Our work also has several limitations. First, GeoAnimation may struggle with more complex geographic data types, such as 3D geographic data, spatio-temporal network data, and hierarchical geographic data. Future work could further expand GeoAnimation's declarative grammar to support more geographic data types and visualization forms. Second, while GeoAnimation provides users with flexible tools for creating geographic animations, it lacks intelligent features like automatic geographic story generation and recommendation. Users still need to manually design and adjust animation content and timelines. In the future, we could leverage large language models to enable automatic generation of geographic stories based on data characteristics and user needs, further enhancing animation production efficiency. Third, when processing large-scale geographic data, GeoAnimation may face performance challenges such as slow rendering speeds and interaction delays, affecting animation smoothness and real-time responsiveness. Going forward, we can optimize GeoAnimation's rendering performance through techniques like data compression, level-of-detail (LOD) rendering, and parallel computing. Beyond these, in the future, we could also implement the grammar as a cross-platform JavaScript library to support web, mobile, and desktop applications.

7 Conclusion

In this work, we present GeoAnimation, a declarative grammar and interactive tool aimed at simplifying geographic animation creation. We analyze 50 geographic data animations to establish a design space and develop a specialized grammar. GeoAnimation enables users to define animations via a JSON format, offering flexibility and ease of use. Our tool supports real-time preview and adjustment, empowering non-professionals to create geographic animations efficiently. Through use cases and expert interviews, we demonstrate its effectiveness in producing expressive geographic animations. This work enhances geographic data visualization and storytelling, lowers creation barriers, and paves the way for future advancements in geographic animation creation.

Acknowledgments

The authors would like to thank the anonymous reviewers for their constructive comments. This work was supported in part by NSFC (62402421) and in part by Ningbo Yongjiang Talent Programme (2024A-399-G).

References

[1] A. Aboulhassan, R. Sicat, D. Baum, O. Wodo, and M. Hadwiger. Comparative visual analysis of structure-performance relations in complex bulk-heterojunction morphologies. In *Computer Graphics Forum*, vol. 36, pp. 329–339. Wiley Online Library, 2017. 2

[2] F. Amini, N. Henry Riche, B. Lee, C. Hurter, and P. Irani. Understanding data videos: Looking at narrative visualization through the cinematography lens. In *Proceedings of the 33rd Annual ACM conference on human factors in computing systems*, pp. 1459–1468, 2015. 2

[3] F. Amini, N. H. Riche, B. Lee, A. Monroy-Hernandez, and P. Irani. Authoring data-driven videos with dataclips. *IEEE transactions on visualization and computer graphics*, 23(1):501–510, 2016. 2

[4] L. Ardissono, M. Delsanto, M. Lucenteforte, N. Mauro, A. Savoca, and D. Scanu. Map-based visualization of 2d/3d spatial data via stylization and tuning of information emphasis. In *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*, pp. 1–5, 2018. 2

[5] P. H. C. Braga and I. F. Silveira. Slap: storyboard language for animation programming. *IEEE Latin America Transactions*, 14(12):4821–4826, 2016. 3

[6] D. Brodbeck, R. Mazza, and D. Lalanne. Interactive visualization-a survey. In *Human Machine Interaction: Research Results of the MMI Program*, pp. 27–46. Springer, 2009. 2

[7] A. Buccella, A. Cechich, J. Porfiri, and D. Diniz Dos Santos. Taxonomy-oriented domain analysis of gis: a case study for paleontological software systems. *ISPRS International Journal of Geo-Information*, 8(6):270, 2019. 2

[8] A. R. Buckley, M. Gahegan, and K. Clarke. Geographic visualization. In *A research agenda for geographic information science*, pp. 313–333. Crc Press, 2004. 2

[9] S. Cao, Q. Chen, and N. Cao. Visual narrative for data journalism based on user experience. *Journal of Visualization*, 27(6):1195–1211, 2024. 2

[10] C. Demetrescu and I. Finocchi. Smooth animation of algorithms in a declarative framework. *Journal of Visual Languages & Computing*, 12(3):253–281, 2001. 3

[11] S. Di Martino, E. Landolfi, N. Mazzocca, F. R. di Torrepadula, and L. L. L. Starace. A visual-based toolkit to support mobility data analytics. *Expert Systems with Applications*, 238:121949, 2024. 2

[12] D. DiBiase, A. M. MacEachren, J. B. Krygier, and C. Reeves. Animation and the role of map design in scientific visualization. *Cartography and geographic information systems*, 19(4):201–214, 1992. 2

[13] D. Fisher. Animation for visualization: Opportunities and drawbacks. *Beautiful visualization*, 19:329–352, 2010. 3

[14] Y. Fu and J. Stasko. More than data stories: Broadening the role of visualization in contemporary journalism. *IEEE Transactions on Visualization and Computer Graphics*, 2023. 2

[15] T. Ge, B. Lee, and Y. Wang. Cast: Authoring data-driven chart animations. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–15, 2021. 1

[16] T. Ge, Y. Zhao, B. Lee, D. Ren, B. Chen, and Y. Wang. Canis: A high-level language for data-driven chart animations. In *Computer Graphics Forum*, vol. 39, pp. 607–617. Wiley Online Library, 2020. 1

[17] Z. Gui, C. Yang, J. Xia, J. Li, A. Rezgui, M. Sun, Y. Xu, and D. Fay. A visualization-enhanced graphical user interface for geospatial resource discovery. *Annals of GIS*, 19(2):109–121, 2013. 2

[18] Y. Guo, N. Cao, L. Cai, Y. Wu, D. Weiskopf, D. Shi, and Q. Chen. Datamator: An authoring tool for creating datamations via data query decomposition. *Applied Sciences*, 13(17):9709, 2023. 3

[19] M. Harrower, S. Fabrikant, and M. Dodge. The role of map animation in geographic visualization. 2008. 2

[20] J. Heer and G. Robertson. Animated transitions in statistical data graphics. *IEEE transactions on visualization and computer graphics*, 13(6):1240–1247, 2007. 3

[21] K. Hyun, K. Lee, and J. Lee. Motion grammars for character animation. In *Computer Graphics Forum*, vol. 35, pp. 103–113. Wiley Online Library, 2016. 3

[22] A. Inc. After effects. `https://www.adobe.com/products/aftereffects.html`, 2022. Accessed on Sep 1, 2022. 2

[23] C. Keßler and E. Lotstein. *Animation as a Visual Indicator of Positional Uncertainty in Geographic Information*, pp. 365–382. Springer International Publishing, 2018. doi: 10.1007/978-3-319-78208-9_19 1

[24] Y. Kim and J. Heer. Gemini: A grammar and recommender system for animated transitions in statistical graphics. *IEEE Transactions on Visualization and Computer Graphics*, 27(2):485–494, 2020. 3

[25] W. Li, Z. Wang, Y. Wang, D. Weng, L. Xie, S. Chen, H. Zhang, and H. Qu. Geocamera: Telling stories in geographic visualizations with camera movements. In *Proceedings of the 2023 CHI conference on human factors in computing systems*, pp. 1–15, 2023. 2

[26] J. Loviscach. Two-finger input with a standard touch screen. In *Proceedings of the 20th annual ACM symposium on User interface software and technology*, pp. 169–172, 2007. 2

[27] D. Mashima, S. Kobourov, and Y. Hu. Visualizing dynamic data with maps. *IEEE Transactions on Visualization and Computer Graphics*, 18(9):1424–1437, Sep 2012. doi: 10.1109/TVCG.2011.288 1

[28] P. Moran and D. Ellsworth. Visualization of amr data with multi-level dual-mesh interpolation. *IEEE transactions on visualization and computer graphics*, 17(12):1862–1871, 2011. 2

[29] T. Nagel and B. Groß. Shanghai metro flow: Multiple perspectives into a subway system. *Leonardo*, 50(5):511–512, 2017. 2

[30] P. Ogao and M.-J. Kraak. Defining visualization operations for temporal cartographic animation design. *International Journal of Applied Earth Observation and Geoinformation*, 4(1):23–31, Aug 2002. doi: 10.1016/S0303-2434(02)00005-3 1

[31] D. J. Peuquet and M.-J. Kraak. Geobrowsing: creative thinking and knowledge discovery using geographic visualization. *Information Visualization*, 1(1):80–91, 2002. 2

[32] N. Pezzotti, J. Thijssen, A. Mordvintsev, T. Höllt, B. Van Lew, B. P. Lelieveldt, E. Eisemann, and A. Vilanova. Gpgpu linear complexity t-sne optimization. *IEEE transactions on visualization and computer graphics*, 26(1):1172–1181, 2019. 2

[33] P. Reipschlager, T. Flemisch, and R. Dachselt. Personal augmented reality for information visualization on large interactive displays. *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1182–1192, 2020. 2

[34] C. W. Reynolds. Computer animation with scripts and actors. *ACM SIGGRAPH Computer Graphics*, 16(3):289–296, 1982. 3

[35] D. Shi, F. Sun, X. Xu, X. Lan, D. Gotz, and N. Cao. Autoclips: An automatic approach to video generation from data facts. In *Computer Graphics Forum*, vol. 40, pp. 495–505. Wiley Online Library, 2021. 2

[36] X. Shu, A. Wu, J. Tang, B. Bach, Y. Wu, and H. Qu. What makes a data-gif understandable? *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1492–1502, 2020. 2

[37] J. T. Stasko. A practical animation language for software development. In *Proceedings. 1990 International Conference on Computer Languages*, pp. 1–2. IEEE Computer Society, 1990. 3

[38] S. Takahashi, S. Matsuoka, K. Miyashita, H. Hosobe, and T. Kamada. A constraint-based approach for visualization and animation. *Constraints*, 3:61–86, 1998. 3

[39] J. Tang, L. Yu, T. Tang, X. Shu, L. Ying, Y. Zhou, P. Ren, and Y. Wu. Narrative transitions in data videos. In *2020 IEEE visualization conference (VIS)*, pp. 151–155. IEEE, 2020. 2

[40] E. Teixeira, J. Giannella, and D. Kosminsky. Animation and data visualization: an analysis protocol proposal. *InfoDesign-Journal of Information Design*, 18(3), 2021. 2

[41] M. Thöny, R. Schnürer, R. Sieber, L. Hurni, and R. Pajarola. Storytelling in interactive 3d geographic visualization systems. *ISPRS International Journal of Geo-Information*, 7(3):123, 2018. 1, 2

[42] Q. Van Ho, P. Lundblad, T. Åström, and M. Jern. A web-enabled visualization toolkit for geovisual analytics. *Information Visualization*, 11(1):22–42, 2012. 2

[43] A. Vondráková. Map symbol design: Presenting abstract topics with advanced symbology. *Abstracts of the ICA*, 2:1–2, 2020. 2

[44] P. C. Wong, K. Zhu, X.-D. Yang, and H. Fu. Exploring eyes-free bezel-initiated swipe on round smartwatches. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–11, 2020. 2

[45] L. Wu, D. Cao, J. Yang, R. Zhang, and X. Yan. The symbolization of regional elements based on local-chronicle text mining and image-feature extraction. *ISPRS International Journal of Geo-Information*, 13(9):299, 2024. 2

[46] M. Wu, Y. Sun, and Y. Li. Adaptive transfer of color from images to maps and visualizations. *Cartography and Geographic Information Science*, 49(4):289–312, 2022. 2

[47] V. Yang and M. Jasim. Animating the narrative: A review of animation styles in narrative visualization. In *2024 IEEE Visualization and Visual Analytics (VIS)*, pp. 321–325, Oct 2024. doi: 10.1109/VIS55277.2024.00074 1, 2

[48] W. Yin, D. Zou, C. Bao, X. Cheng, J. Wu, W. Xiao, D. Wang, Z. Zhou, and Q. Lan. An interactive data visualization design based on webgis. In *2019 IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC)*, pp. 2462–2465. IEEE, 2019. 2

[49] L. Yu, L. Harrison, and A. Lu. Effectiveness of feature-driven storytelling in 3d time-varying data visualization. *Journal of Imaging Science & Technology*, 60(6), 2016. 2

[50] J. Zong, J. Pollock, D. Wootton, and A. Satyanarayan. Animated vega-lite: Unifying animation with a grammar of interactive graphics. *IEEE Transactions on Visualization and Computer Graphics*, 29(1):149–159, 2022. 1, 3