GeoAnimation: A Grammar for Animated Geographic Visualization

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Abstract

Animated geographic visualization is a common way to communicate spatial processes and narratives. However, authoring such animations often requires tradeoffs among learnability, control, and production effort. To explore a structured authoring approach, we analyzed 64 source videos containing geographic animation segments and synthesized a design space for geographic animation targets, attributes, and effects. Based on this analysis, we designed GeoAnimation, a domain-specific declarative grammar and interactive prototype for authoring common point, line, and region animations. We examined the prototype through two use cases and expert interviews with two visualization researchers. The results provide preliminary evidence that GeoAnimation is feasible for the studied authoring tasks, while broader usability, expressiveness, and performance require further evaluation.

Keywords: Geographic Animation, Animation Creation, Geographic Visualization, Grammar

1 Introduction

Geographic animation dynamically visualizes geospatial information and processes [1, 2]. As part of narrative visualization [3–5], it combines maps, visual encodings, temporal change, and storytelling techniques [1, 4, 5]. Such animations are used in domains such as weather forecasting, traffic simulation, urban planning, education, and online public communication.

However, creating geographic animations remains difficult. Tools such as Canis [6], CAST [7], and Animated Vega-Lite [8] provide important abstractions for chart or general visualization animation, and they can be extended or applied to map-based graphics when geographic elements are represented as marks, encodings, or keyframes. Still, they do not directly expose geographic authoring primitives such as map context, spatial target categories, coordinate and geometry attributes, or route- and region-specific effects. Authors therefore often need to manually encode geographic semantics when adapting these tools. Animators may also use video production software such as Adobe After Effects [9]. These tools are flexible, but they provide limited support for geographic data semantics, so authors must manually prepare, align, and animate map elements. This process can be time-consuming and error-prone.

The limitations above have motivated us to explore an interactive authoring approach centered on a domain-specific grammar for geographic animation. GeoAnimation focuses on geographic authoring primitives that make spatial semantics explicit: point, line, and region targets; map-style and view parameters; spatial attributes such as coordinates, geometry, color, size, opacity (i.e., transparency), and images; temporal sequencing through durations, timelines, and keyframes; and reusable effects organized by target type. In this study, our aim is to develop this grammar and an accompanying interactive prototype so that authors can define and preview common geographic animation designs through structured declarations. Nevertheless, achieving this goal faces the following two challenges.

Identifying Geographic Animation Primitives. Geographic animations combine map context, spatial objects, visual encodings, and temporal narrative stages. Identifying reusable primitives therefore requires systematic coding of animation examples rather than only inspecting final frames.

Lack of Intuitive and Effective Tools. An authoring tool must also help authors edit grammar instances, validate their specifications, and preview the resulting map animations. The interface and grammar therefore need to be developed together.

To address the first challenge, we analyzed 64 source videos containing geographic animation segments, extracted recurring design elements and techniques, and constructed a design space for geographic animation. Based on this design space, we designed a JSON-based declarative grammar for geographic animation. The grammar encodes global timing and map style, element-level spatial attributes, and keyframe-based temporal behavior for point, line, and region targets, and it provides reusable effects such as point motion and diffusion, line growth and flow, and region highlighting and color fill. To address the second challenge, we developed an interactive tool that supports grammar editing, real-time validation, and map-integrated preview, allowing authors to iteratively adjust the structured specification and observe the resulting geographic animation. We named the grammar and tool GeoAnimation.

To examine the feasibility of GeoAnimation, we present two use cases and formative interviews with two visualization researchers. The use cases illustrate how the grammar can express representative point, line, and region animations in the studied scenarios. The interviews provide expert feedback on the grammar, prototype workflow, and possible extensions.

The main contributions of this study are as follows:

- A design space that characterizes geographic animation through geospatial targets and visual animation effects grouped by changing attribute.
- A domain-specific declarative grammar for geographic animation that models map context, spatial attributes, temporal sequencing, keyframes, and reusable point, line, and region animation effects, together with an interactive editor and map-integrated preview system for authoring grammar instances.
- A preliminary evaluation through two use cases and formative expert interviews that examines the feasibility of GeoAnimation for the studied authoring tasks.

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 help communicate spatial information and support knowledge discovery, especially for complex geographic datasets [5, 10, 11]. Effective geographic visualization presents spatial data while also guiding audiences through the story behind the data [5, 12].

Early geographic visualization research emphasized static map design [13]. Interactive geographic visualization later expanded this focus by supporting exploration through operations such as zooming, filtering, and selection [14–19].

Storytelling has also become an important topic in geographic visualization [20, 21]. Prior work has studied narrative structures, cinematic techniques in data videos, transition design, and animation for visual storytelling [4, 22–24]. In geographic settings, Thöny et al. [5] explored storytelling methods for interactive 3D geographic visualization systems.

Camera movement is another important narrative device for geographic animation. GeoCamera [25], for example, supports exploratory analysis through camera path animation. Beyond camera techniques, systems such as DataClips [26] and AutoClips [27] automate aspects of data-video authoring. These systems mainly target general data videos or camera-path exploration rather than grammar-based geographic animation authoring. GeoAnimation complements this work by focusing on structured map objects, timeline control, and reusable geographic effects.

Accordingly, GeoAnimation explores an interactive approach for specifying and previewing map context, spatial targets, temporal sequencing, and reusable geographic effects.

2.2 Visualization Animation Grammar

In visualization, grammars provide reusable abstractions for specifying visual structure and behavior, helping authors express designs consistently and compactly [28–30].

Animation can represent temporal and spatial patterns and support storytelling, but it also introduces challenges such as cognitive load and implementation complexity [31]. Animation grammars address part of this challenge by describing animations through reusable elements and operations [32, 33]. Related systems such as Gemini, Animated Vega-Lite, and Datamator show how grammar-based or declarative approaches can support animation authoring in statistical graphics and data videos [8, 34, 35].

Early studies addressed general-purpose animation descriptions, such as TRIP [36], and animated transitions in statistical graphics [37]. Later work explored animation syntax for specific visualization types. Gemini describes animated transitions between statistical charts and recommends transition designs [34], while Animated Vega-Lite treats animations as time-varying data queries within the Vega-Lite abstraction [8].

These works suggest that animation grammars can be generalized across visualization types or specialized for particular authoring needs. GeoAnimation follows the latter direction. Existing grammars may be used for map-based animations when geographic content is encoded as generic visual marks or visualization states, but they do not directly model map context, geospatial targets, spatial attributes, and target-specific effects. GeoAnimation instead provides structured point, line, and region objects, timeline and keyframe control, reusable geographic effects, and synchronized map preview.

3 Design Space

This section describes how we collected geographic animation examples and synthesized the resulting design space.

3.1 Data Collection

To identify recurring design patterns, we collected source videos from online sources, segmented them into short clips, and coded the clips by target type, visual attribute, and animation effect.

Corpus Construction. We constructed a corpus of 64 source videos from well-known YouTube channels and other online sources. We began with geography-related explainer and data-journalism videos, then expanded the corpus through platform recommendations, related-video links, and web searches for geographic data animations and interactive map-based stories. We included only videos containing explicit geographic animation segments, such as animated maps, moving spatial targets, changing regional attributes, routes, or spatial narratives. The final corpus contains 58 YouTube videos and six non-YouTube source videos: two Bilibili videos, one The Paper video, one BuzzFeed video, and two New York Times videos. The complete source list and URLs are provided in the supplemental corpus file.

Video Segmentation. We segmented each source into atomic animation units when the geographic target, animation effect, visual attribute, or narrative stage changed. Each valid segment contains at least one geographic information element. We capped each segment at 10 seconds to keep clips manageable and comparable during coding; longer sequences were split into multiple units when they contained multiple narrative stages or repeated effects.

Statistics and Analysis. We then analyzed the coded clips to identify recurring visual attributes and effects. Position, size, color, and opacity were the most common dimensions of change. We also grouped effects by the geometric target to which they apply: points, lines, or regions.

3.2 Results

The resulting design space has two dimensions: geospatial targets and visual animation effects. Their combination defines the major animation patterns observed in the corpus, as shown in Figure 1.

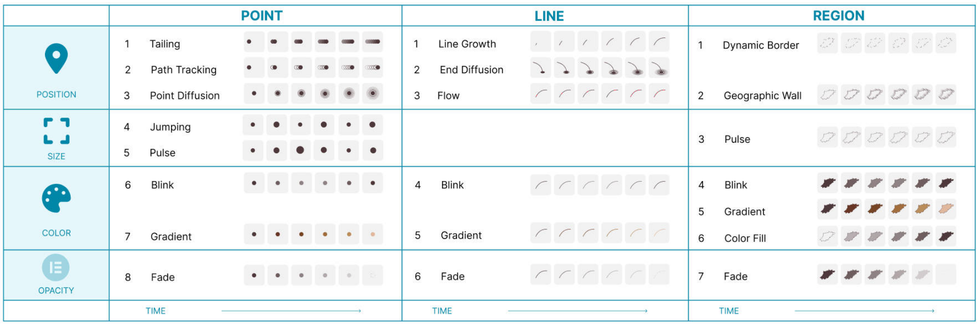

Fig. 1 Design space of geographic animation effects. Columns show geospatial target types (point, line, and region), rows group effects by the changing visual attribute (position, size, color, and opacity), and the thumbnails illustrate the temporal progression of each effect from left to right.

3.2.1 Geospatial Targets

We categorize geospatial targets into three geometric types: points, lines, and regions. Point targets represent locations or events, such as cities, monitoring stations, or emergency sites. Line targets represent connections, paths, or flows, such as transportation routes, rivers, migration paths, or data transmission lines. Region targets represent areas with attributes or boundaries, such as administrative divisions, ecological zones, urban areas, or climate regions.

3.2.2 Visual Animation Effects

Visual animation effects describe how target attributes change over time. We organize the observed effects by the changing attribute: position, size, color, and opacity.

Position-Related Effects. For point targets, tailing and path tracking show motion trajectories, while point diffusion shows spread from a location. For line targets, line growth, end diffusion, and flow describe route construction, expansion, or movement along a path. For region targets, dynamic borders and geographic walls emphasize boundaries or selected areas.

Size-Related Effects. Jumping and pulse effects change the size of a point or region to draw attention or show fluctuation.

Color-Related Effects. Blink effects draw attention through rapid color change, gradient effects show continuous change, and color fill defines or updates region categories and attributes.

Opacity-Related Effects. Fade effects apply to point, line, and region targets and support scene transitions, staged reveal, or emphasis changes.

These effects provide the empirical basis for the grammar constructs described in the next section.

3.3 Summary

Through this analysis, we summarized a design space centered on geospatial targets and visual animation effects. It provides the empirical basis for the GeoAnimation grammar, while also reflecting the scope of the corpus: common geographic animation practices in online explainer, data-journalism, and interactive map-based examples.

4 GeoAnimation

Following the design space and prior work on animation grammar, we designed GeoAnimation as an initial declarative grammar and prototype for geographic animation authoring. The grammar operationalizes common point, line, and region animation patterns from our corpus.

4.1 Declarative Grammar

We established two design goals grounded in the design-space analysis and prior work on geographic animation, narrative visualization, and animation grammar. Our design space shows that geographic animations commonly organize spatial targets through temporal changes in position, appearance, emphasis, and map context. Prior studies similarly identify time, sequence, and animated transitions as central to communicating geographic change and visual narratives [1, 2, 4, 5, 10], while animation grammars emphasize concise abstractions for specifying dynamic visual behavior [8, 34, 37].

G1: Support temporal sequencing for geographic narratives. Time in geographic animation may represent measured temporal change, such as traffic volume over time, or event-sequence narratives, such as the staged appearance of locations, routes, barriers, and regions. GeoAnimation therefore uses duration, element-level timelines, and keyframes to coordinate the appearance, transformation, and disappearance of geographic elements.

G2: Provide a concise grammar for common geographic animation patterns. We intentionally prioritize a JSON-based grammar for common point, line,

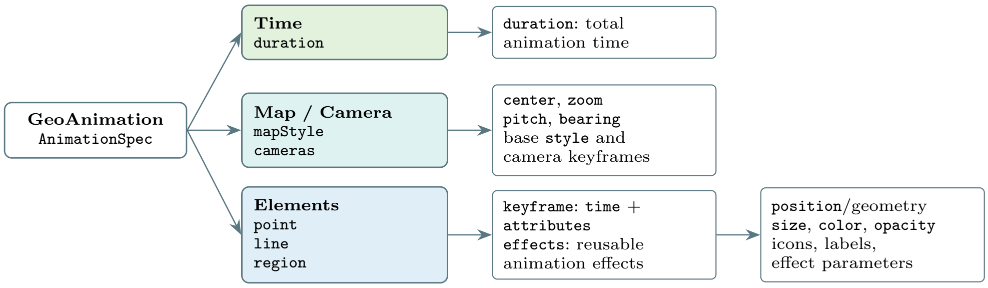

Fig. 2 Schematic structure of the GeoAnimation grammar. A specification defines global time, mapstyle and camera parameters, and an array of point, line, or region elements. Each element combines keyframed temporal attributes with reusable animation effects.

and region animations identified in the design space. This choice helps authors define animations through structured spatial attributes, keyframes, and reusable effects without writing low-level animation code. The resulting conciseness also creates an expressiveness tradeoff, which we discuss in Section 6.3.

Based on these goals, the grammar links spatial attributes with time, as summarized in Figure 2. Its central construct is the keyframe: authors mark when elements appear, change, or disappear in the JSON structure, and the system interpolates the corresponding visual states.

Time is specified at two levels. The global `duration` field defines the total animation length, while the `time` array within each element's `keyframe` controls element-level changes. For example, a point can start moving at 300 ms while a line starts drawing at 500 ms, creating a staged sequence.

The JSON structure is hierarchical. The top layer defines global parameters such as `duration`, `mapStyle`, optional `cameras`, and the `elements` array. Each point, line, or region element then defines its own spatial attributes, keyframes, and effects. Composite sequences can be created by combining simple element-level actions, such as appearing, blinking, and moving at different times.

By associating visual attributes with keyframes, GeoAnimation allows authors to specify temporal change without writing time-calculation code. For example, a region's fill color can change over time, or a line can grow along a route. The design borrows the timeline concept from animation software while keeping the specification organized around geographic targets and attributes.

4.2 System

The prototype uses a dual-view layout: a JSON editor on the left and a map preview on the right, as shown in Figure 3. This design supports iterative editing and previewing of grammar instances.

In the editor, authors write or modify the JSON specification. The system validates the JSON in real time and provides feedback for syntax or parameter errors. It also supports insertion of colors, location coordinates, and images; for example, authors can click on the map to obtain geographic coordinates.

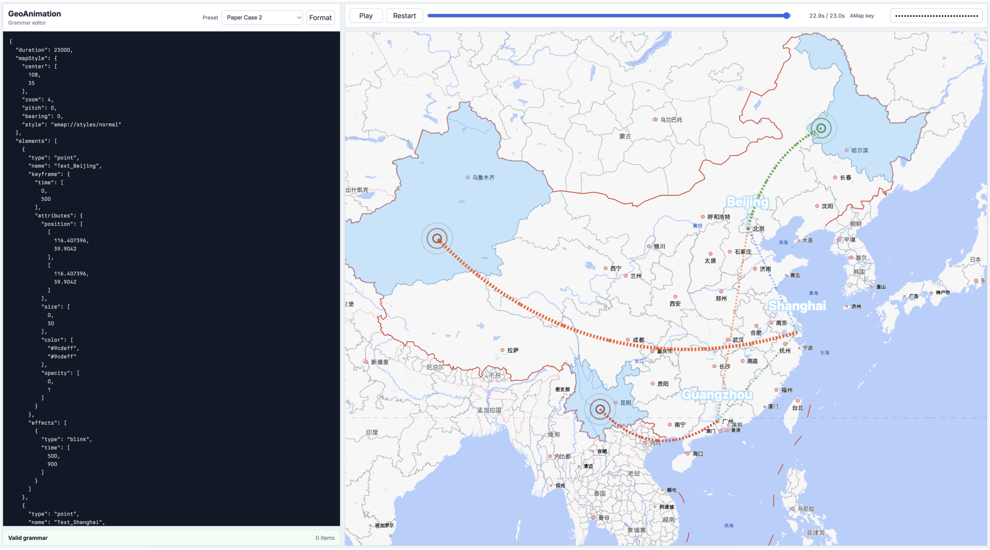

Fig. 3 GeoAnimation prototype interface. The left panel provides JSON grammar editing, preset selection, formatting, and validation feedback, while the right panel provides playback controls and a synchronized map preview of the generated geographic animation.

The map view renders the resulting animation and supports map interactions such as panning, zooming, and rotating. It also supports multiple visualization layers for combining geographic elements.

The two views are synchronized: when the JSON changes, the map preview updates accordingly. This feedback helps authors connect the declarative specification with the generated animation.

The system also provides templates for common scenes such as point movement, line drawing, and region highlighting. Authors can load and modify these examples instead of starting from an empty specification.

Overall, the prototype provides an initial environment for authoring and refining point, line, and region animations. Its broader usability and expressiveness remain topics for future study.

5 Evaluation

This section examines GeoAnimation through two demonstrative use cases and formative expert feedback. The use cases illustrate representative geographic animation sequences, while the expert interviews gather initial feedback on the grammar and prototype workflow. The evaluation is intended to demonstrate feasibility for the studied scenarios rather than broad usability or authoring effectiveness.

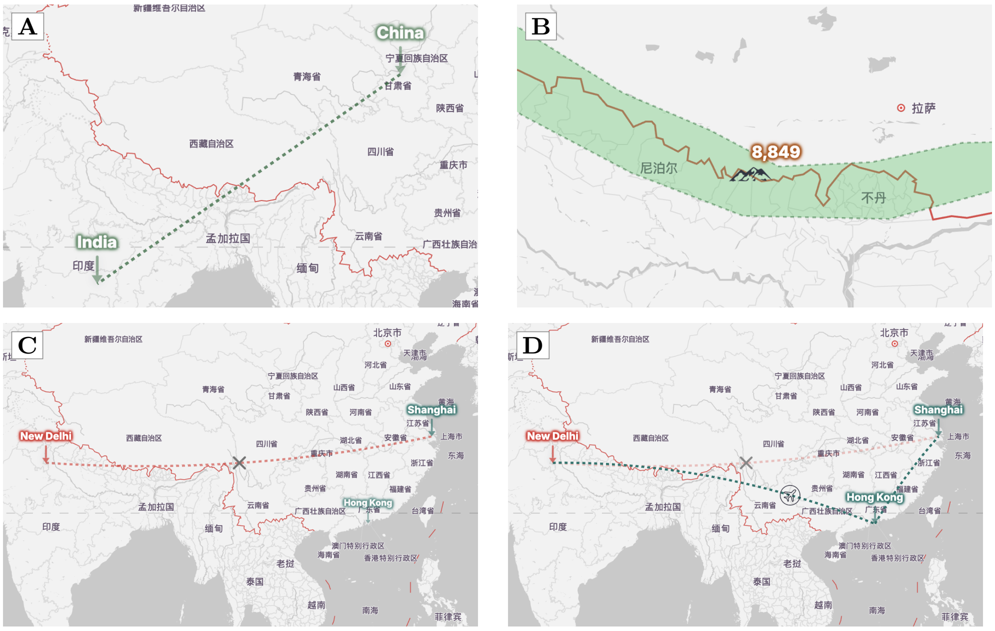

Fig. 4 Progressive animation for the China–India air-route case. (A) Point targets label India and China, connected by a line target to introduce the spatial relationship. (B) A mountain icon, numeric height label, and region emphasis highlight the Himalayan barrier. (C) A line target between New Delhi and Shanghai is interrupted to indicate that a direct route is constrained by the Himalayan mountains. (D) Alternative route lines connect New Delhi, Hong Kong, and Shanghai, with an aircraft icon showing the transfer path.

5.1 Use Cases

We selected two representative 2D geographic data visualization scenarios. The first case focuses on a cross-border air-route narrative that combines point, line, and region targets. The second case focuses on a transportation-network narrative that coordinates city points, route lines, and regional emphasis. Together, the cases cover the major target categories in our design space and use common effect categories such as motion, route drawing, highlighting, color or opacity change, and staged temporal sequencing.

5.1.1 Case I: Geographic Visualization of the China–India Air Route

This case presents the geographic relationship between China and India and the transportation challenges between them. The animation focuses on how mountain barriers and route constraints shape air travel between the two countries.

The animation begins by marking China and India as point targets and connecting them with a line target, establishing the basic spatial relationship between the two countries. The author then reduces the opacity of the initial point and line elements as a transition to the main geographic constraint: Mount Everest and the Himalayan region between China and India.

To present this geographic challenge, the author places an icon at Mount Everest and changes its size over time. A numeric height label is introduced beside the icon, while dynamic border and color-fill effects emphasize the surrounding region and boundary.

After presenting the geographic barrier, the author shifts to flight-route issues. The animation marks New Delhi, Shanghai, and Hong Kong, then draws route lines among them. Growth effects are applied to the lines so that potential flight routes gradually extend across the map.

Finally, the animation focuses on a New Delhi–Hong Kong–Shanghai transfer route. An aircraft icon is added to make the transfer path more direct and readable.

Through this four-step progression, shown in Figure 4, the case combines point, line, icon, region, and temporal effects to present the geographic constraints behind the China–India flight-route narrative.

5.1.2 Case II: Dynamic Interconnection of Transportation Networks among Cities in China

This case illustrates China's transportation network, focusing on connections among Beijing, Shanghai, and Guangzhou.

At the beginning, the author starts from the system templates and locates three points representing Beijing, Shanghai, and Guangzhou on the map. The coordinate assistance in the system helps place these points accurately, and blink effects emphasize their roles as major transportation hubs.

Subsequently, the author establishes connections between each pair of cities by drawing route lines for Beijing–Shanghai, Beijing–Guangzhou, and Shanghai–Guangzhou. Route-growth effects simulate the gradual development of transportation routes, and flow effects represent continuous movement along these routes.

To enhance dynamics, the author introduces mobile elements such as freight and passenger trains. These elements move along the routes with tails, visually representing the continuous flow of goods and people between cities, as shown in Figure 5(A).

The story develops as surrounding regions are introduced. Dynamic border and color-fill effects emphasize the areas associated with the major transportation hubs, as shown in Figure 5(B).

As the video develops, the author expands the transportation network beyond the original three cities. New railway lines start from Beijing, Shanghai, and Guangzhou and extend to other regions such as Heilongjiang, Xinjiang, and Yunnan. These routes are accompanied by the end-diffusion effect, as shown in Figures 3 and 5(C), symbolizing the expanding scope and influence of China's transportation infrastructure.

Overall, the case uses a multi-stage sequence: it starts from city locations, expands to intercity connections, and then presents a broader national network. Different colors, widths, and motion effects distinguish routes and regions across the sequence.

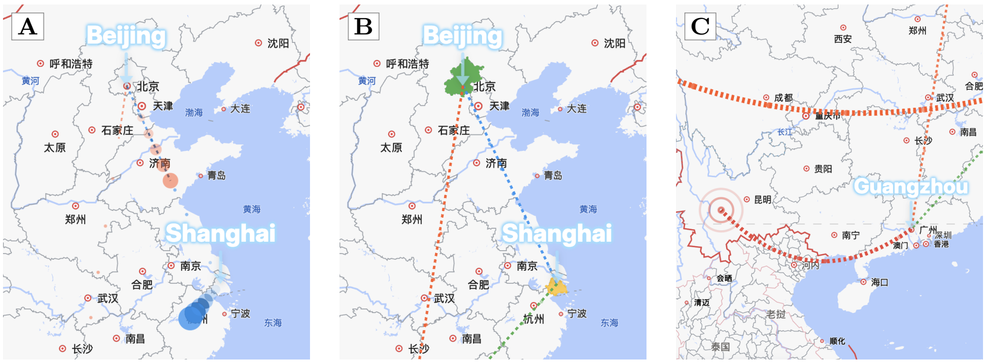

Fig. 5 Animation effects in the China transportation-network case. (A) Point targets with tail effects represent moving trains or vehicles along routes between cities. (B) Region targets use color fill to emphasize the areas associated with major transportation hubs. (C) A line target uses end diffusion to show the outward expansion of a transportation route.

5.2 Expert Interview

To collect formative feedback, we conducted expert interviews. We first describe the participants and procedure, then summarize the feedback.

5.2.1 Participants and Procedure

We invited two visualization researchers to participate in the interviews. Both have experience in geographic visualization authoring and geographic data visual analytics. One participant had 10 years of relevant visualization and geographic visualization experience, and the other had 8 years of relevant experience. Although both participants were familiar with geographic visualization, they were not specialists in geographic data storytelling or geographic animation authoring; we therefore interpret their feedback as formative expert input rather than as evidence of expert animation-production performance.

Each session lasted about 30 minutes. We spent about 15 minutes introducing the research background, grammar design, and two use cases, followed by about 15 minutes of hands-on exploration. During the exploration, participants used provided datasets to create animations for point, line, and polygon features and to orchestrate temporal sequences in which animation effects appeared one by one. They began from predefined JSON templates and then edited the JSON specifications directly. Finally, we conducted semi-structured interviews about the prototype workflow, perceived usefulness, limitations, and possible extensions.

5.2.2 Feedback

We collected the feedback from the experts and summarize it as follows.

Ease of learning and use. The experts considered the template-based starting points and JSON editing workflow understandable during the short exploration period. They noted that the real-time map preview helped them connect changes in the specification with the resulting animation, and that the validation feedback could help authors identify syntax or parameter problems while iterating. These observations suggest that the combination of templates, direct JSON editing, and map-integrated preview is a promising workflow for the studied authoring tasks.

Effectiveness. Experts commented on the expressiveness of GeoAnimation for the demonstrated cases. They found that the two examples could be implemented through the grammar and that the available point, line, and region elements covered common operations in the explored scenarios. They also noted the value of explicit temporal sequencing and geographic transformation parameters for composing multi-stage animations. At the same time, this feedback reflects expert judgment from a small formative study and should not be read as a measured comparison with existing tools or as evidence of general user performance.

Suggestions. Experts also suggested improvements. They noted that the grammar could be extended to support heatmaps, flow maps, and 3D maps; that rendering performance should be examined for larger geographic datasets; and that future versions could include AI-assisted story generation or recommendation.

6 Discussion

This section discusses implications, lessons learned, limitations, and future work.

6.1 Implications

Our work carries the following implications. First, GeoAnimation suggests how a domain-specific grammar can structure common geographic animation tasks. By making map context, spatial targets, keyframes, and reusable effects explicit, the grammar provides a way to specify the animation logic behind point, line, and region narratives. Second, the design space offers a vocabulary for discussing geographic animation effects. It decomposes observed examples into targets, attributes, and effects, which can support both grammar design and analysis of existing animations. Third, the approach may be useful in scenarios such as education, data journalism, public communication, weather and disaster reporting, urban planning, and GIS workflows. In these contexts, authors often need to communicate spatial relationships and temporal progressions to broad audiences.

6.2 Lessons Learned

We derived three lessons from the design process. First, coding geographic animation requires careful segmentation: long videos and subtle effects can obscure changes in target, attribute, or narrative stage. Slowing down playback and checking clips frame by frame helped reduce omissions. Second, grammar design benefits from organizing specifications around authoring intent. Our early design scattered data and effects across separate components, which made revisions cumbersome. The current structure groups spatial attributes, keyframes, and effects by geographic element, closer to how authors plan animation sequences. Third, a small prototype can still be useful when it focuses on core authoring actions. In GeoAnimation, the JSON editor, validation, templates, and synchronized map preview support a narrow but coherent workflow for common geographic animation patterns.

6.3 Limitations and Future Work

Our work also has several limitations. First, the current grammar and prototype have clear design boundaries. They support point, line, and region targets; spatial and visual attributes such as coordinates, geometry, size, color, opacity, and images; map-style and camera parameters such as center, zoom, pitch, and bearing; timeline and keyframe control; and reusable effects including point movement, path tracking, diffusion, line growth, flow, dynamic borders, color fill, blink, fade, and geographic walls. They do not yet directly model heatmaps, dense flow maps, large spatio-temporal networks, full 3D terrain or extrusion visualizations beyond the current camera and wall primitives, or hierarchical geographic data. Future work could extend the grammar with time-varying raster or color-scale layers for heatmaps, aggregated line groups with width, speed, and direction encodings for flow maps, richer camera and extrusion primitives for 3D maps, and nested data structures for hierarchical geographic entities. Second, although our corpus includes 64 source videos from multiple online sources, it is still dominated by YouTube videos and may overrepresent explainer and data-journalism styles. Future work should expand the corpus to include more sources from professional GIS workflows, educational materials, scientific visualization, public-sector communication, and interactive web maps. Third, the current evaluation is limited. It includes two demonstrative use cases and interviews with two visualization researchers. Although the participants had experience in geographic visualization authoring and geographic data visual analytics, they were not specialists in geographic data storytelling or geographic animation authoring. Future work should include a larger task-based study with both expert and non-expert users, compare GeoAnimation with existing authoring workflows, and collect quantitative measures such as completion time, error rates, learning effort, and perceived workload. Fourth, the current study does not include a formal performance benchmark. When processing large-scale geographic data, GeoAnimation may face performance challenges such as slow rendering speeds, interaction delays, and reduced animation smoothness, especially for many simultaneous elements, dense geometries, or frequent keyframe updates. Going forward, we can optimize GeoAnimation's rendering performance through techniques such as geometry simplification, tiling, caching, level-of-detail (LOD) rendering, and parallel rendering. Fifth, GeoAnimation does not yet include intelligent features such as automatic geographic story generation or recommendation. Authors still need to design and adjust animation content and timelines manually. Future work could explore large language models for suggesting geographic narratives or draft animation specifications from data characteristics and author goals. Finally, the grammar could be implemented as a cross-platform JavaScript library for web, mobile, and desktop applications.

7 Conclusion

In this work, we present GeoAnimation, an initial declarative grammar and interactive prototype for geographic animation authoring. We analyze 64 source videos containing geographic animation segments to establish a design space and develop a grammar for common point, line, and region animation patterns. GeoAnimation allows authors to define animations in JSON and preview the results in a synchronized map view. Through two use cases and formative expert interviews, we provide preliminary evidence for the feasibility of this approach in the studied tasks. Future work should extend the grammar, broaden supported visualization types, improve scalability, and conduct larger-scale user evaluation.

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