Spatiotemporal Phenomena Summarization through Static Visual Narratives

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***Abstract*—Information visualization commonly aids the understanding of the evolution of spatiotemporal phenomena. The current work proposes a novel approach to visually represent spatiotemporal phenomena based on the automated generation of static and interactive visual narratives that summarize the evolution of a spatiotemporal phenomenon. The visual narrative is composed of an interactive storyboard that consists of a set of frames that represent events of interest in the phenomenon. Towards corroborating the hypothesis that this approach would effectively and efficiently transmit the evolution of spatiotemporal phenomena, we conceptualized a visualization framework, identifying visual metaphors that map spatiotemporal transformations into visual content and defining the parameterization approaches for spatiotemporal features. We developed a functional prototype implementing the conceptual solution and presented issues encountered regarding visual clutter and parameterization. We conducted a user study based on a questionnaire which concluded that the proposed approach can be effective and efficient for understanding the evolution of these phenomena in terms of transformations for a subset of possible scenarios.**

***Index Terms*—spatiotemporal visualization, static visual narratives, spatiotemporal phenomena, events of interest**

I. Introduction

Nowadays we have the technology to automatically collect, store, retrieve and represent vast quantities of data regarding spatiotemporal phenomena or, in other words, objects that exist in space and for which multidimensional attributes change over time [1]. Information visualization frameworks are often used towards easing the perception, communication, and analysis of spatiotemporal data [2], [3] through meaningful static or dynamic representations [4].

Static representations are not dependent on viewer time, meaning the visual contents do not change over time automatically (e.g., charts). Instead, modifications that occur to the visualization result from user interaction. Dynamic representations are dependent on viewer time, meaning the visual contents change as a function of time itself as they are being displayed (e.g., animations).

The problem addressed in this work encompasses some issues that we identified for each type of visualization. The first problem concerns the linearity of time-mapping in dynamic visualizations: dynamic visualizations often linearly map the temporal aspect of the data into the duration of the visual contents. The mapping function can either expand, shorten or maintain the time interval of the data to accommodate analysis in a timely manner, while generally also allowing the user to change the play speed at any time.

Considering the previously described behaviour, the user, not having prior knowledge of the phenomenon, would consume the entirety of the visualization in order to understand the evolution of the object. Although skipping or increasing the play speed can be alternatives, their usage can lead to the loss of perceived detail while decreasing the play speed can result in more time spent analysing the data. Moreover, there are three specific scenarios that can be problematic with these approaches: the occurrence of sudden transformations whose effects do not last might be imperceptible to the user, resulting in loss of perceived detail; the occurrence of fine-grained transformations that might not be perceived by the user, despite being of interest, due to their small changes; the existence of long periods of object immutability or slow occurring transformations, resulting in increased time spent analysing the behaviour of the phenomenon.

The second problem concerns the challenge of representing object dynamism in static visualizations. For a long time, spatial and temporal data have been represented through static visualization media, such as comics [5]. However, there has not been a predominant method for statically representing data with both spatial and temporal variables (spatiotemporal data). This fact comes from the inherent difficulty of conveying the dynamism of an object in a static fashion. This is a limitation that, although less problematic for displaying a small number of transformations (e.g., teaching geometric transformations in computer graphics books [6]), it carries difficulties in the creation of a static visual narrative that explains the story of an object that goes through numerous distinct or compound transformations.

Finally, we came across the challenge of filtering through events of interest: through filtering, a user can disregard irrelevant information for a given task or data domain to improve the efficiency of the visualization framework.

However, to the best of the researched knowledge, in the domain of spatiotemporal information, there has not been conceptualized a framework that would allow users to filter through the transformations that occurred to the object.

Towards proposing a solution to the aforementioned issues, various visualization methods were studied (II) and a novel visualization framework was conceptualized (Section III), prototyped (Section IV), and evaluated (Section V).

II. Literature Review

To conceptualize a solution to the issues presented in the previous section, three topics were studied: information visualization representations, event-oriented approaches to summarize spatiotemporal phenomena, and visual narratives as a means to tell a story with data.

Visual representations data can be distinguished between static and dynamic. Static representations of time-dependent data include a variety of charts and graphs (e.g., index charts, stacked graphs, horizon graphs, circle graphs, spiral graphs, and more [7], [8]). However, these methods are not suited for incorporating the spatial dimension as a variable as well. However, some visual representations use the spatial dimension for contextualizing the data, as seen in *Lexis Pencil* visualization [7]. Static representations of space-dependent data have multiple visualization methods based on variations of maps like choropleth maps, graduated symbol maps, and cartograms which aggregate data per geographic region [8] and are thus unsuitable for representing spatiotemporal phenomena in terms of geometric transformations. Towards this goal, two static visualization methods were analysed: flow maps and isochrone maps. Flow maps are capable of representing movement and quantity in space and time through the use of flow lines [9]. On the other hand, isochrone maps, generally used for representing areas of equal travel times, can be adapted to depict object area changes by drawing each snapshot of the object [10], for example, using progressively more saturated colours. Dynamic representations essentially encompass animations and videos. When considering space-dependent data, Geographical Information Systems (GIS) become an option to dynamically visualize geographical data [11], possibly in real-time.

Towards developing an event-oriented visualization framework [12], the concept of *event of interest* was studied and adapted. This concept allows defining, depending on the task or type of data, which spatiotemporal events are of interest. The authors Tominski, Schulze-Wollgast, and Schumann introduced two types of parameters to define events of interest [13]:

1) Parameters that define a threshold for the value of a given feature. These parameters mark an event when the value of a feature in a certain timestamp exceeds the defined threshold: $V_t > \Delta$.
2) Parameters that define a threshold on the variation of the value of a given feature between two consecutive time steps. These parameters mark an event when the difference in the value of a feature from one time step to the next surpasses the defined threshold: $V_t - V_{t-1} > \delta$.

Sections III and IV further explore the parametrization of spatiotemporal events of interest used in this work.

In order to visually tell the story of a spatiotemporal phenomenon using data, the concept of visual narratives — visual contents that narrate a story [14] — was briefly studied. As seen with visualization frameworks, Pimenta and Poovaiah [14] presented a dichotomy between static and dynamic visual narratives. Static visual narratives are composed of a set of visuals that remain unchanged on the medium while dynamic visual narratives feature visuals that constantly change over time. The authors describe that narratives, regardless of being static or dynamic, can be interactive. Interactive visual narratives can be impacted by user interaction, resulting in the unfolding of the story or the update of the visual contents. Moreover, according to Segel and Heer, visual narratives can be designed to balance the narrative intended by the author(s) with story discovery by the reader [15]. These authors describe this balance with a spectrum from author-driven to reader-driven storytelling approaches. Purely author-driven narratives tell the story the author wants to be told, heavily relying on messaging and disregarding viewer interactivity. Purely reader-driven narratives do not enforce the order of the visual contents shown to the reader which, by means of interactivity, can freely discover the story. When adapting the previous concepts to data-and-event-driven visual storytelling, the viewer is free to analyse the visual contents and discover the spatiotemporal events that occurred. The current work is based on the generation of static interactive visual narratives and adopts a hybrid model in regards to Segel and Heer's classification, enforcing the order of the events in the spatiotemporal phenomenon story, but allowing the user to freely explore it through interactivity.

III. Conceptual Visualization Framework

To address the issues listed in Section I, we propose a novel visualization framework that automates the generation of static and interactive visual narratives that can visually summarize the evolution of a spatiotemporal phenomenon. The static visual narrative is supported by an interactive storyboard composed of a set of frames that render a visual representation of the user-defined events of interest of the phenomenon.

Figure 1 shows an example of a spatiotemporal phenomenon visualized through the developed functional prototype of the proposed solution. The example depicts a translation which occurred slowly, a small period of immutability and a fast-occurring transformation that encompassed both a translation and scale.

A. Events of interest

To conceptualize a solution based on events of interest, a set of parameters were defined for each spatiotemporal feature. The scope for this work was to support 2D geometric transformations, including translations, scales, and orientation changes (rotations around the centroid of the object). The parametrization of these transformations was adapted from the approach seen in Section II, utilizing the following parameters:

1) **Delta threshold** (δ) — A *delta threshold* is a value that triggers an event when the absolute difference between

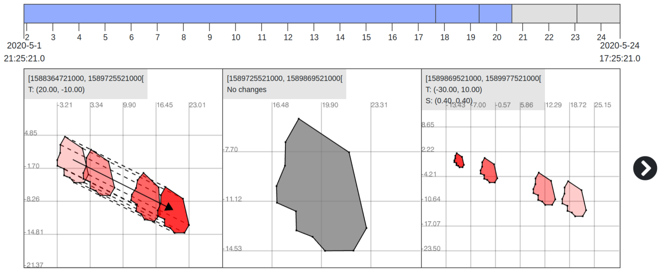


Fig. 1: Illustration of a prototype of the proposed solution

feature values (e.g., translation vector magnitude) of two consecutive timestamps is greater than the delta threshold: $|V_t - V_{t-1}| > \delta$.

2) **Absolute cumulative threshold (Δ_{abs})** — An *absolute cumulative threshold* is a value that triggers an event when its internal accumulator value surpasses the absolute cumulative threshold: $C_{abs_t} > \Delta_{abs}$. The internal accumulator is incremented with each timestamp with the absolute difference in feature value from the last timestamp ($|V_t - V_{t-1}|$).
3) **Directed cumulative threshold (Δ_{dir})** — The *directed cumulative threshold* uses the same logic as the absolute variant ($C_{dir_t} > \Delta_{dir}$), differentiating in the way the internal accumulator treats values from new timestamps. The internal accumulator is incremented with each timestamp with the difference in feature value from the last timestamp, as long as the feature's *direction* is maintained. If the *direction* changes between timestamps (e.g., a growing object starts shrinking), the accumulator value is reset.

To define if these types of spatiotemporal events are of interest, the user would specify any of the three parameters which are all optional and the absence of every parameter means the object change itself is not of interest to the user.

However, not all spatiotemporal features can be parameterized by the aforementioned metrics. Features related to the temporal aspect, such as *immutability*, can be parameterized through a minimum time period (e.g., minimum object immutability period to mark an immutability event).

B. Visual elements

After selecting the data and setting the event of interest parameters, the user sees the static visual narrative generated using the template described in this section.

The visual narrative is organized as a storyboard composed of a set of static frames, where each frame visually represents an object transformation (or multiple overlapping transformations). The *main storyboard*, illustrated in Figure 1, considers the entire time interval of the dataset and displays all the transformations identified with the parameters set by the user.

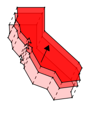
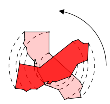
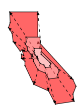
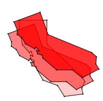
By clicking on any frame, a new storyboard is displayed beneath it, revealing which transformations occurred for the time interval of that frame, considering more granular parameters which should provide more fine-grained visual results. With these parameters, it may be possible to get more frames since these fine-grained parameters are easier to be reached thus revealing more granular transformations. The term that refers to this process is *zooming in on a frame*, resulting in a hierarchical layout, illustrated in Figure 2.

Fig. 2: Hierarchical layout design

As stated, each storyboard frame visually represents one or more spatiotemporal events. Towards this end, a set of visual metaphors (shown in Table I) was designed to convey each type of classified transformation that can occur to the object. The recurring usage of onion skinning is due to its ability to denote acceleration by drawing intermediate states with a visual variable that can be ordered (e.g., colour saturation and transparency). The usage of arrows can provide intuitive information regarding the direction and magnitude of the transformation. The usage of vertex mapping can provide resilience towards the expected noise that the object's vertices can suffer. Two types of transformations were introduced, multiple and unknown transformations. The former was added since events can overlap and, in those scenarios, a frame of type *multiple transformations* is presented. The latter's purpose is to be a fallback frame type for when it was either not possible to classify which transformation occurred or the transformation is not supported by the visualization framework.

Providing temporal, spatial, and narrative contexts was also a concern in the conceptualization of the proposed visualization framework. Temporal and narrative contexts are provided with a *timeline object*. The timeline object is composed of two distinct elements: a narrative progress bar and a timeline. The narrative progress bar aids the user in contextualizing the frames being presented to the screen in relation to the complete narrative. It is composed of rectangles — progress items —, each representing a frame in the storyboard regardless of whether or not the frames are currently visible to the user. The other primary responsibility of this element is to provide relative temporal context. The term *relative* refers to representing the duration of each frame *in relation to* the duration of the narrative. Progress items use an accent colour for frames that are being displayed, leaving the rest

TABLE I: Visual metaphors for each spatiotemporal feature

Feature	**Visual metaphor**	**Visual metaphor design elements**
Translation		• Onion skinning (using transparency) • Translation vector • Vertex mapping
Orientation		• Circular path arrow • Circular vertex mapping
Scale		• Onion skinning (using colour saturation and based on isochrone maps) • Vertex mapping with scale direction arrows
Immutability		• Absence of colour saturation
Multiple transformations		• Onion skinning (using transparency)
Unknown transformations		• Onion skinning (using transparency) • Absence of colour saturation

of the progress items of the narrative greyed out. Highlight colours are used for progress items that correspond to frames that are being hovered or zoomed-in. The timeline element temporally contextualizes the narrative frames in absolute terms, in contrast to the narrative progress bar which does so in a relative manner. Having both elements juxtaposed, the user can assert when a frame starts and ends, and, consequently, when the story begins and finishes.

Providing spatial context is equally essential in spatiotemporal visualization so users can spatially reference objects. Despite base maps being the ubiquitous choice for spatial contextualization in geovisualization [10], spatiotemporal visualization is used in more fields. Therefore, to avoid tight coupling with geographical data, the envisioned solution features a grid system to spatially contextualize the overlaid objects. The grid is displayed behind the object and contains reference values agnostic to the unit of length. Additionally, the grid divisions are not constant throughout the storyboard to reflect scene dimension changes from one frame to another.

To fulfil exact-value information needs of scientific visualization, a frame overlay was designed to supplement the visual contents. The overlay, present in each frame, displays the frame's time interval and describes the transformation that occurred to the object and its units through a textual representation.

IV. Visualization Prototype

Towards assessing the feasibility of the presented visualization framework, a functional prototype was developed as part of a system that is composed of an object change quantification server and a client visualization application. The visualization prototype implements the conceptual framework proposed in Section III. The server component is also a prototype of a conceptual framework that identifies and quantifies object change of spatiotemporal phenomena using the concept of events of interest [16], providing the necessary event-based input for the visualization component.

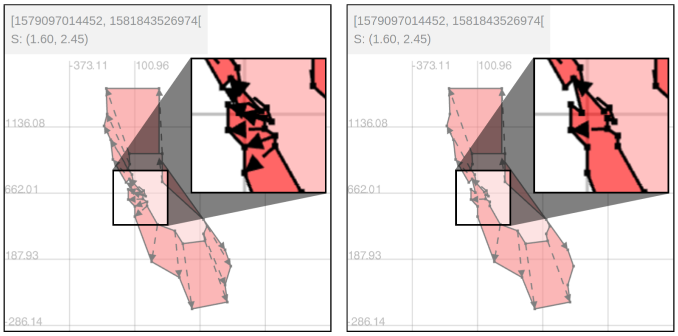
Throughout prototype development and testing, a new type of frame was devised: *unimportant changes*, meaning the lack of transformations encompassed by the spatiotemporal features of interest. Before the introduction of *unimportant changes*, "time gaps" existed between frames in some scenarios. For example, between two spatiotemporal events there might be a time interval in which small changes occur that do not surpass any of the thresholds and would otherwise leave a temporal gap in the narrative. The display of full temporal continuum was considered relevant to avoid lack of interpretation of what happened in-between frames. The frames that fill in those gaps are referred to as *unimportant changes*, having the same visual metaphor as an *immutability*.

Furthermore, two new types of parameters were brought to light during the development and testing of the prototype: *noise epsilon* and *detail threshold multiplier*. Noise epsilon is a parameter that was created due to precision errors in the quantification server that would lead to the identification of very small transformations that didn't actually occur. To overcome this weakness, this parameter was added to translations, orientation changes, and scales. To filter this noise, transformations only start to be considered as such once the noise epsilon is surpassed.

A detail threshold multiplier is a type of parameters that are set for each spatiotemporal feature and defines how the other parameters are adjusted when a storyboard frame is zoomed-in for more detail. Various possibilities exist towards lowering the parameters. The approach chosen for this work is a non-linear function that has a horizontal asymptote along the x-axis to avoid the parameter reaching a value of zero: $y = p \cdot m^x$, where x is the depth in the hierarchical storyboard, y is the parameter value to be used to retrieve the new frames, p is the initial parameter set by the user, and m is the detail threshold multiplier (which should be in the interval $]0, 1[$).

A troublesome aspect that was noticed through testing the prototype was the visual clutter caused by the elements of the visual metaphors, particularly onion skinning. To address this problem, elements such as vertex mapping and arrows were made able to be disabled.

The visual clutter caused by vertex mapping occurred mostly in objects that have sections with a large density of vertices (illustrated in Figure 3a). To mitigate this type of visual clutter and still accommodate users unwilling to fully disable vertex mapping, a solution was implemented based on polygon simplification. Through polygon simplification, it was possible to automatically mark which vertices are *more relevant* which would then be used for the visual metaphors, reducing the previously mentioned clusters of vertices (shown in Figure 3b). At an implementation level, the polygon simplification process utilizes a sequence of two algorithms: Radial Distance and Ramer-Douglas-Peucker [17], [18].



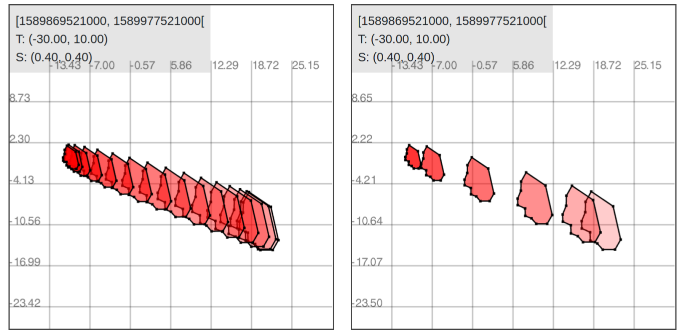
(a) Before polygon simplification (b) After polygon simplification

Fig. 3: Same frame rendered without (left) and with (right) polygon simplification

Onion skinning also caused visual clutter, mostly in frames which had numerous object states. Before, all the available intermediate states were drawn, causing overlapping between them and thus visual clutter (illustrated in Figure 4a). To mitigate this problem, a solution was devised by naively and manually limiting the number of intermediate states (shown in Figure 4b). To decide which object states were displayed to the user, two constraints were imposed: all displayed states must be equally spaced in terms of time, and the first and final states must always be displayed. Since it is expected the states returned by the server to be equally spaced in time, it becomes a problem of retrieving, at most, n (number of intermediate states set by the user) equally spaced items of the state array. However, this array problem does not have a possible solution for all combinations of the maximum number of intermediate states and the total number of states (e.g., when $n < 6$ and there are 8 states in total, only the initial and final states are drawn).

V. Evaluation

To evaluate the effectiveness of the proposed solution, a user study was conducted through a questionnaire which was answered by 33 students. Regarding the structure of the questionnaire, it was divided into six sections, each serving a different purpose. Besides the introductory and observations sections, the other four can be seen as two separate parts of the questionnaire with two sections each. The first part concerning storyboard frames as individual elements, analysing the identification of transformations through the visual metaphors in individual frames and the interpretation of transformation units. The second part addressed the narrative as a whole, assessing the interpretation of complete narratives and compared its usage with dynamic visual narratives.



(a) Before intermediate state limitation (b) After intermediate state limitation ($n = 4$)

Fig. 4: Same frame rendered without (left) and with (right) intermediate state limitation

The first part of the questionnaire had good results with the majority of users correctly identifying transformations and its units. However, most users struggled to specify the order of intermediate states if the object, for example, shrunk and then grew (which could be represented in the same frame if it triggers the absolute cumulative threshold for scales).

The second part of the questionnaire revealed difficulties in understanding the timeline element. On the other hand, the results of object story interpretation with the proposed static visual narrative were promising since most subjects understood the transformations that occurred to the object, its units, duration, and order. The second half of this part compared the proposed solution with a dynamic visual narrative (an animated video). This comparison revealed that, with the dynamic counterpart, users had difficulties in perceiving small or fast transformations, as well as when multiple transformations occurred simultaneously. On the other hand, in general, users manifested difficulty in understanding storyboard rows that appear when zooming in frames when they represent events that overlap each other.

From the feedback gathered in the questionnaire, users prefer the effortlessness and intuitiveness of an animation video for simple and short spatiotemporal phenomena as long as no fast or small-to-detect transformations occur. On the other hand, the majority of subjects affirm the visualization framework is more suitable for conveying scientific information due to better accuracy and efficiency at telling the story of the object. Users state that the proposed method should be applied to cases with complex phenomena, fast occurring or potentially imperceptible transformations, or stories lasting for long periods of time. Finally, there seems to be another dichotomy in the users' opinions: the majority who values freely exploring the data and some who consider it a level of indirection that leads to a disconnection of the event itself.

VI. Conclusions and Future Work

Based on the results obtained in the evaluation of the visualization prototype, the following research questions were answered:

1) **Are static visual narratives effective in describing the evolution of a spatiotemporal phenomenon?** According to the results from Section V, static visual narratives are effective at telling the story of an object. It was considered by users to be suitable for scientific visualization since its individual frames contain the necessary information to identify transformations, its units and duration. Considering the complete narrative of a phenomenon, users were also capable of describing it with high accuracy with the exception of interpreting the meaning of zoomed-in frames and some difficulties regarding the timeline.
2) **Are static visual narratives efficient when compared to their dynamic counterpart?** The evaluation stage revealed that static visual narratives can outperform dynamic approaches in scenarios with potentially imperceptible transformations — either due to its fast pace or small units of transformation — or for data that spans for long periods of time. These advantages match the limitations of dynamic visualizations presented in Section I. On the other hand, dynamic visual narratives such as animated videos are still relevant and preferred by some users for simple and short spatiotemporal phenomena.

Considering the answers given to the research questions, we concluded that summarizing spatiotemporal phenomena through static visual narratives can be an effective and efficient method for understanding the evolution of these objects in terms of transformations for a subset of possible scenarios.

With these promising conclusions, we suggest future work to further explore or improve the proposed visualization framework at a conceptual level:

1) Exploring different layouts: for example, a hierarchical layout that would gradually decrease the detail of the visual metaphors and the frame's relative size for the storyboard rows closer to the root.
2) Studying methods for mitigating visual clutter: for example, mitigating visual clutter in onion skinning through state overlapping heuristics.
3) Studying methods for visually representing the temporal dimension, since some users refer a disconnection between the transformations that occurred to the object and their duration.
4) Studying multi-layered user interfaces — interfaces that have multiple layers of complexity —, accommodating both a general public and industry specialists [19].
5) Improving the visual metaphors, especially concerning *multiple transformations* since this type of frames does not feature visual metaphors that are related to its individual transformations. Furthermore, the visual metaphors for transformations could also depend on the type of threshold that triggered the event.
6) Conducting improved evaluation, for instance by using probability sampling methods [20] and performing user studies that depend on direct interaction of subjects with the prototype.

Moreover, some aspects of the proposed overall system could be improved by extending the change quantification server component which would result in more topics to be explored for the visualization framework, such as supporting more spatial transformations, dependent variables, temporal events, and derived variables.

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