There and then: interacting with spatio-temporal visualization

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***Abstract*—Interactivity plays a crucial role in Information Visualization (InfoVis). Together with the visual representation, interaction allows the user to implicitly form mental models of the relationships within the data, identify patterns, and pursue analysis hypotheses. To make the most of it, it is vital to fully understand what opportunities and limitations interactivity arise in different contexts. Spatio-temporal (ST) data sets are often extensive and challenging to analyze and display. Although interaction is essential to mitigate the inherent challenges concerning ST visualization, there has been little research on its specificities. In this paper, we scrutinize these specificities by conducting a case study: we applied a generic interaction taxonomy for InfoVis to 25 examples of ST visualization of reference and performed the necessary adjustments towards a new specialized taxonomy, according to the triad Theme, Time and Space.**

I. Introduction

The role of interactivity in InfoVis is evident. Interactivity is even at the core of the most widely accepted definition of InfoVis: "the use of computer-supported, interactive, visual representations of abstract data to amplify cognition" by Card, Mackinlay, and Shneiderman [1]. Therefore, the use of interaction has been extensively studied in InfoVis research.

The purposes for interactivity in InfoVis are numerous, ranging from making the data more engaging or playful, to presenting the data in flexible portions, for instance, by partitioning it, allowing the user to browse it or query it. This flexibility is particularly important when exploring large data sets [2], where decreasing the level of complexity of the data is vital for its proper understanding and analysis.

However, most research on interaction techniques addresses InfoVis in general, and there has been little research on the specificities of particular visualization usage contexts, such as ST visualization. The articulation of temporal and spatial dimensions is extremely powerful and appealing, allowing users to interpret the evolution of events both in time and space. Moreover, it has several areas of application, ranging from more exploratory scenarios to communication contexts. Therefore, it also arises particularly complex visualization problems.

Exploratory scenarios consider the visualization as a discovery tool, where it is necessary to provide ways for users to find the answers that the author did not anticipate and/or provided. On the other hand, communication contexts provide an editorial intention and present answers to what the author believes to be the users' interest, such as in data journalism.

Nevertheless, the usual size and complexity of data represented in ST visualization is a challenge, and frequently purely visual solutions are insufficient and need to be combined with further interaction techniques, such as filtering, data aggregation, and disclosure of additional details.

In this paper, we explore which are the specificities of the use of interaction in ST visualization by applying a generic interaction taxonomy for InfoVis, proposed by Figueiras [3]. As a sample, we used 25 examples of ST visualization of reference, previously identified by Rodrigues [4] and performed a systematic analysis of the interaction techniques applied. After identifying the elements that were infeasible to adapt to the ST context, we implemented the necessary adjustments to the existing taxonomy, resulting in a new specialized taxonomy that assumes the structural triad Theme, Time, and Space as the conceptual focus.

II. Background and Related Work

The visualization of changes within the data and its dynamic properties tend to be the center of attention of a new generation of interactive visualizations [5] because of its potential of engagement. Time and space are two fundamental aspects of human existence. Everything that exists and everything that happens is located in both time and space.

A. Interaction in spatio-temporal visualization

The visualization of ST information arises complex problems but it is essentially through the observation of object transformation or its movement that we perceive the passage of time [6]. Incorporating interactivity in InfoVis presents various advantages, such as the extension of the natural limit of what can be made visible in the interface; the increase of the quantity and variety of analytical perspectives to satisfy different needs and curiosities; the efficiency manipulating the available data to answer several types of questions; and more control of the discovery experience and its potential for customization [7]. As general InfoVis, ST visualizations are primarily dynamic and often include interaction techniques, which are crucial for the manipulation of the temporal and spatial variables within the data set.

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1	filtering	Display only data in which I am interested.
2	selecting	Mark or track items in which I am interested.
3	abstract / elaborate	Adjust the level of abstraction of the data.
4	overview and explore	Overview first, zoom and filter, then details-on-demand.
5	connect / relate	Show how this data is related.
6	reconfigure	Give me a different arrangement of the data.
7	encode	Give me a different representation of the data.
8	history	Allow me to retrace the steps I take in the exploration.
9	extraction of features	Allow me to extract data in which I am interested.
10	participation / collaboration	Allow to contribute with data.
11	gamification	Show me the data in a more playful way.

Table I: InfoVis interaction taxonomy by Figueiras [3]

At the turn of the 21th century, the visualization of ST information was a rising topic of research in InfoVis. The technological advances in Geographic Information Systems (GIS) and the new facilities for visualizing the time variation of spatially referenced data sets lead to an uptake in interest on the topic. It resulted in representation frameworks [6], conceptual models [8], and theoretical foundations for ST analysis and interaction [9–11]. Since then, the enthusiasm with ST visualization within the InfoVis community has decreased, remaining few authors outside the GIS community. Specific software has been developed and improved, and tools such as Axismaps, ArcGIS, or Jiku allow the common user to create dynamic stories with maps, adding the temporal variation. Notwithstanding, scarce research is being conducted to stabilize the field and deeply understand the possibilities and specificities of interactive ST visualization.

B. Existing Taxonomies of Interaction

Designing a taxonomy is challenging mostly because of the rapid development of the area. Nevertheless, there are already several proposed for interaction techniques in generic InfoVis [2, 12–14], the most well-known being the *Visual Information-Seeking Mantra* by Shneiderman [15]. For this study, we adopted the InfoVis interaction taxonomy proposed by Figueiras [3], due to its broadness and inclusion of more modern interaction techniques, such as participation or gamification. Further, we adapted its 11 interactive techniques into operative criteria for the present analysis. The chosen reference taxonomy is illustrated in Table I and each component will be explored in more detail in Section IV.

III. Methodology

To understand the specificities of interaction usage in ST visualization, we applied the referenced taxonomy [3] to the 25 selected cases of study by Rodrigues [4], listed in Table II. The selection of the sample followed a key premise: the visualizations needed to be necessarily interactive, extrapolating elementary interactions, such as video play, pause or stop.

Ref.	Title	Year
a	NEO – NASA Earth Observations	2005
b	Flightradar24	2006
c	MarineTraffic	2007
d	Snow Plows in New York City	2013
e	NASA Worldview	2013
f	Foursquare Time Machine	2013
g	HubCab	2014
h	The Refugee Project	2014
i	In Flight	2014
j	Child Lives	2014
k	U.S. Daily Temperature Anomalies	2014
l	World City Populations 1950-2035	2015
m	When Do Americans Leave for Work?	2015
n	ImagineRio	2015
o	Shipmap	2016
p	The History of Urbanization	2016
q	Boom to Bust	2016
r	E3 – Eruptions, Earthquakes & Emissions	2016
s	Two Centuries of U.S. Immigration	2016
t	Es War Nicht Immer der Osten	2017
u	Airbnb Is Growing Fast	2017
v	Peak Spotting	2017
w	Digital Atlas of Innovation	2017
x	London AirBnB bookings, Summer'18	2019
y	Singapore Calling	2019

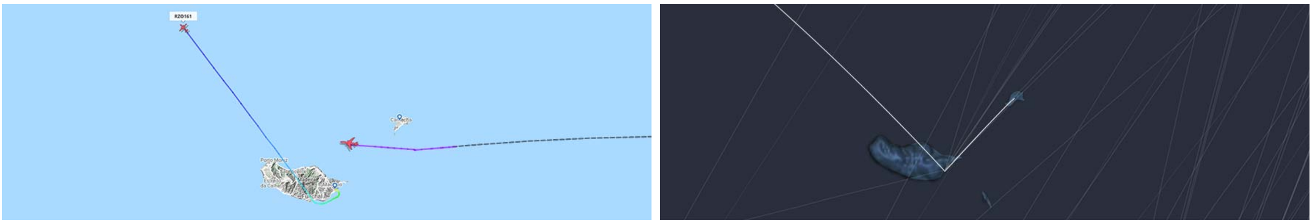
Table II: Cases of study used by Rodrigues [4]

The case study method was chosen because of its exploratory and iterative nature, with no hypotheses established *apriori*. The 25 cases were analyzed individually using a Google Chrome V. 79.0.3945.117 web browser, on a 28" monitor (2560x1440px).

Early on in the study, it was observed that the 11 interaction techniques would apply differently in the distinct dimensions of ST visualization, varying the implications for the user experience. Therefore, to achieve a more stable and dedicated analysis, we attempted the decomposition of each interaction technique in the three dimensions of the ST triad: Theme, Time, and Space. For instance, the technique *filter* can be related to thematic, temporal, or spatial data, providing three distinct tasks, e.g., to filter objects with determined characteristics; to filter moments of interest; or to filter results relative to a given location. Moreover, we have also decided to breakdown the technique *abstract/elaborate* [3] into the three smaller tasks comprised in it: *zooming, details-on-demand*, and *linking*.

Additionally, some rules for the analysis had to be established beforehand. To begin with, it is mandatory to clarify that all criteria correspond to acts triggered by interactions. Interpretative insights must not be confused with interactive techniques. For instance, the possibility of identifying relationships and connections may be achieved through the visual representation alone, or provided by specific tasks to *connect/relate* different elements. In the same way, in ST visualization, the fact that it is possible to compare two or more moments, geographical areas, or thematic objects, is not exclusively supported by interaction tasks deliberately designed for this purpose.

Also, a few authors assume broader interpretations on the intention of experience regarding the interaction technique



(a) *Encode* in *b.Flightradar24*: Path from sum of coordinates (ad.) (b) *Reconfigure* in *i.In Flight*: Route from connecting two points (ad.)

Figure 1: Example of the distinction between the usage of the interaction techniques *encode* and *reconfigure*

filtering. In this study, we applied the task as defined by the taxonomy's author [3], meaning that a *filter* requires the corresponding information layer to be added to the base map if the data point fulfills its parameters. In opposition, more substantial changes, such as alternating between different types of thematic maps or switching to a simplified view, correspond to the interaction technique *encode*, implying the modification of the visual representation. Moreover, the act of transposing a map into another type of visualization, such as a scatter plot (as found in case *a* of Table II), was not considered an *encode* because the resulting chart does not include the variables Space and Time simultaneously, thus exiting the ST context.

The terminology regarding *filtering* and *selecting* also needed to be clarified due to a common confusion between the act of selecting and the homonym interaction technique. That is, selecting one moment in time, as found in cases *t* or *j*, was classified as *filtering* because what the user is actually doing while performing the interaction task is omitting the remaining non-selected information. To be considered *selecting* in this study, the information would have to remain visible and highlighted, allowing the user to compare the selected items with the whole. Likewise, there is a match between pausing or selecting one moment in time with the technique *filter* because it restricts the visualization to single moments, where all other timestamps are hidden.

The act of changing the speed of the unfolding events might influence the users' perception: when time is slowed down, the level of abstraction is adjusted, allowing the user to apprehend more profound details of the visualization; when time is speeded up, the information becomes more abstract and details are lost, making, for instance, a moving dot to appear to be a line. Therefore, the possibility of changing the pace was considered here as zoom. Albeit using different mechanics, when the visualization allows manual control over the time variation, we considered it also analogous to *zooming* because, it manipulates the speed at which the events unfold. However, in the cases when the user may freely move the cursor over the temporal scale, we classified it as *reconfigure*, since it shifts the chronological order, along with the pace.

Analyzing the data resorting to different maps may encompass different interaction techniques. We assigned to the category *encode*, interactions that show the accumulation of every location over the entire time interval, generating a new type of map. For instance, the case *b* is a dynamic dot density map of flights that may be perceived as a network map when presenting the full picture. Here, the path results from the sum of all coordinates over the entire time interval. A detail can be seen in Figure 1a. On the other hand, a *reconfigure* occurs if the map shows the representation of a relationship rather than the trajectory of an object. Example of this would be showing the beginning and the end of a route, linked by an arch, or the connections between people located in different parts of the globe. In this case there is a constraint in the data visualized, trimming it to the first and last data points, instead of encoding the original data, as exemplified in Figure 1b.

For the purpose of this study, the technique *linking* encompasses complementary information that directly feeds the visualization experience. This includes supporting content on the topic or procedural material, such as the code libraries used or technical details. This excludes the off subject actions such as linking to social media profiles or sharing.

The ST context arises specific implications regarding the intention of *overview*. For the purpose of this analysis, we considered an *overview* to be any interaction task that brings into view the whole dataset, meaning all data points, in all timestamps and for all locations. For this reason, following here the decomposition rule adopted for the remaining techniques, into Theme, Time, and Space, was unsuitable. Instead, interactions regarding *overview* were divided into *overview-first*, *overview-last*, and *overview-on-demand* according to the intended experience.

The same happened with the technique *history*. Retracing the steps taken in the exploration would have to consider as many categories as there are components in the visualization, regardless of being related to Theme, Time or Space. The *history* would register actions such as the omission of one or more categories through *filtering*; *selection* of one object and tracking its development between two moments; *relate* two or more events; and present the visited hyperlinks.

IV. Results and discussion

From the case study, we were able to achieve four different types of results: the decomposition of the original interaction tasks into Theme, Time, and Space; the patterns identified in the analysis matrix obtained from the 25 cases of reference; the holistic comprehension of the conceptual domain drawn from the analysis itself; and a derivation of the original taxonomy in Table I, now adapted to the context of ST information.

A. Decomposing into Theme, Time, and Space

The eleven categories in the taxonomy by Figueiras [3] were individually analyzed. We broadly assessed the specificities for interaction in the context of ST visualization, considering hypothetical scenarios beyond the ones found in the sample.

As previously stated in Section III, we ascertained that *overview* and *history* would not suit to the decomposition into Theme, Time and Space. The technique *overview* was instead broken down into *overview first*, *overview-last*, and *overview-on-demand*. Further, in its turn, *history* was not decomposable at all, since it is related with the process of exploring the visualization and not dependant on the data.

We have observed that the techniques *filtering*, *selecting*, *connect/relate*, *reconfigure*, and *encode* fulfill the three dimensions of the triad framework [6].

As predicted in Section III, *filtering* materializes clear hypotheses in the ST context. For Theme, this means the possibility of visualizing only objects with specific values or characteristics. In the case of Time, by allowing the choice of a moment or time interval. The dimension Space may be filtered to visualize results of a geographic area of interest.

The interaction technique *selecting* also proved to be easily decomposable. In what concerns Theme, *selecting* in ST visualization encompasses the possibility of marking and tracking one or more items in order to make a distinction from the remaining data. This distinction can also be applied to the dimension Time by *selecting* a precise moment, for example to contrast a time point of a movement within its path. On its turn, when a specific area is in some way highlighted from the rest of the context, we considered it *selecting-space*.

In what concerns *connect/relate* in ST visualization, we identify this interaction technique on Theme when the user is allowed to compare and search for relationships between two different objects or events. When he/she compares values for the same object at various moments, a *connect/relate* in Time is established. Finally, the comparison of data from two distinct locations grants *connect/relate* in Space.

A *reconfigure-theme* provides a new arrangement of the information on the topic. Example of this would be the variation between relative and absolute data, allowing new perspectives for analysis. A *reconfigure-time* is also possible. For instance, switching from a cyclic order to a linear scale; displaying time points or time intervals; playing the progress in reverse; or altering the pace in which the animation flows. A *reconfigure-space* would be feasible in scenarios where the user is allowed to rearrange the geographical position of a location. Although the use of this manipulation may be uncommon, it is relevant, for example, to understand the distortions introduced by map projections, as seen in TheTruesize[1].

In its turn, an *encode-theme* could allow the variation of the thematic components. For instance, changing the colors or shapes of the graphic elements displayed could be a strategy to enhance legibility and/or accuracy of the data exploration. A different visual code for the temporal structure would allow the visualization to accommodate different time conventions. Although in a remote scenario, an *encode-time* would enable the user to switch from the Gregorian calendar to the Chinese calendar, for example. Similarly, an *encode-space* offers a different visual appearance of the geographical components, e.g. the alternation between different thematic maps, geographical views (globe/planisphere), or map projections.

In contrast, a breakdown in the interaction technique *zooming* is possible, but only in two of the three dimensions: Time and Space. Interacting with ST visualization is very intuitive in what concerns the temporal dimension. *Zooming-time* induces in the user the feeling of approximation on the temporal scale by stretching or retracting the amount of detail. Example of this would be varying the granularity of the time unit or changing the pace of the animation. Likewise, *zooming* in Space influences the level of detail of the spatial information displayed on the map view, through the well-known actions of zooming-in and zooming-out. On its turn, *zooming-theme* in ST visualization, is only possible in one conceptual level and will be further analyzed in Subsection IV-C.

According to Peuquet [6], "any effective spatiotemporal representation must take the special properties of space and time into account". Nevertheless, in what concerns interaction techniques, we have concluded that five of the 13 considered are independent from the dimensions Time and Space: *details-on-demand*, *linking*, *extraction of features*, *participation/collaboration*, and *gamification*.

According to the logic of the conducted exercise of decomposition, these techniques would apply exclusively to Theme. In ST visualization, *details-on-demand* is still materialized through the display of further informative details. This accounts for complementary graphics or textual, visual, and other narrative elements. In its turn, *linking* provides either internal paths for cross-referencing objects, or external links to related content, such as articles, videos, reports, downloadables, forums, and blogs. The *extraction of features*, such as datasets, video clips, images, color palettes or code blocks, are also always necessarily subjected to the thematic data. Similarly, more complex interaction techniques, such as *participation/collaboration* and *gamification* are restricted, as well, to Theme. *Participation/collaboration* takes shape when the visualization includes resources provided by contributors, such as collaborative reasoning, or submission of short narratives. These contributions are thus blended in the visualization, contributing to the Theme. As for *gamification*, it can be materialized in the ST context in the form of Quizzes, Dare to Compare the data with the users' reality, or short challenges of guessing Who, What, Where, and When.

Creating a taxonomy that fulfills the criteria of completeness is a difficult task. There may be undiscovered scenarios that allow the decomposition of the interactions into the triad for which we were not able to find an example or hypothesis for. Hence, we assume the taxonomy to be complete at the time of writing. The taxonomy shall naturally be expanded if future scenarios not currently covered are later found.

[1]https://thetruesize.com/

Interaction techniques	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y
filtering | THEME	·	x	x	·	x	·	·	x	·	·	·	·	·	x	x	·	·	x	·	·	·	x	x	·	·
filtering | TIME	x	x	x	x	x	x	x	x	·	x	x	·	x	x	x	x	x	x	x	x	·	x	x	x	x
filtering | SPACE	x	·	·	·	·	·	x	x	·	·	·	·	·	x	·	·	·	·	·	·	·	·	·	·	·
selecting | THEME	·	x	x	·	x	·	·	·	·	·	·	x	·	·	·	·	·	·	·	·	·	x	·	·	·
selecting | TIME	·	·	x	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
selecting | SPACE	·	·	·	·	x	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
zooming | THEME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
zooming | TIME	x	x	x	·	x	·	·	·	·	·	x	·	·	·	·	·	·	x	·	·	x	x	·	x	·
zooming | SPACE	x	x	x	·	x	·	x	x	x	x	x	x	x	x	x	·	·	x	·	x	x	·	x	x	·
details-on-demand | THEME	x	x	x	·	x	x	x	x	x	x	x	x	x	x	·	x	x	x	·	x	·	x	x	·	·
details-on-demand | TIME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
details-on-demand | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
linking | THEME	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	·	x	x	x	x	·	x	·	x
linking | TIME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
linking | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
overview | *FIRST*	·	·	·	·	·	·	·	·	·	·	x	·	·	·	·	·	·	·	·	·	·	·	x	·	·
overview | *LAST*	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	x	·	·	·	·	x	·	·	·	·
overview | *ON-DEMAND*	·	·	x	·	·	x	x	·	x	·	·	x	·	·	x	x	·	x	·	·	x	·	·	·	·
connect/relate | THEME	x	x	·	·	·	·	·	·	·	·	·	·	·	x	·	·	·	·	·	·	·	·	·	·	·
connect/relate | TIME	·	·	·	·	x	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
connect/relate | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
reconfigure | THEME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	x	·
reconfigure | TIME	x	x	x	x	x	x	x	x	x	·	x	·	x	x	x	x	x	x	x	x	·	x	x	x	x
reconfigure | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
encode | THEME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
encode | TIME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
encode | SPACE	·	x	x	·	x	·	·	·	·	·	·	·	·	·	x	·	x	x	·	·	·	x	·	·	·
history	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
extraction of features | THEME	x	x	x	·	x	x	·	x	·	x	x	x	x	·	·	x	x	x	·	x	x	·	·	x	·
extraction of features | TIME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
extraction of features | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
participation/collaboration | THEME	·	x	x	·	·	x	·	·	·	·	·	·	·	·	·	x	·	·	·	·	·	x	·	·	·
participation/collaboration | TIME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
participation/collaboration | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
gamification | THEME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	x	·	·	·	·
gamification | TIME	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
gamification | SPACE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

Figure 2: Matrix exhibiting the results of the conducted case study

B. Analyzing the matrix

In Figure 2 we present our study matrix. From this analysis, we observed that some interaction techniques are intuitive and frequently applied in the context of ST visualization, such as *filtering-time*, *zooming-space*, the display of *details-on-demand*, and *reconfigure-time*. Additionally, two interactions nondependent on Time or Space, *linking* and *extraction of features*, were also frequently observed. On the other hand, authors are rarely incorporating more complex interactions, such as *participation/collaboration* and *gamification*. This was an expected reservation since these techniques are necessarily laborious. The incorporation of these kinds of techniques concerns the structural foundations of the visualization itself. Hence, the effort to include features that actively rely on the user's sophisticate engagement may not be taken lightly.

Some techniques could be further explored. Rodrigues [4] previously pinpointed that the ST context is a privileged scenario for the different interpretations categorized by Kirk [16]: comparisons and proportions, trends and patterns, relationships and connections. The generalization of the usage of the technique *connect/relate* would be able to reinforce these purposive interpretations. On its turn, *selecting* in order to track specific elements in the visualization was mildly adopted. The same happened with *encode*, where the option for different visual codes was only found for the geographical components, in the form of *encode-space*. In what concerns the *overview*, we observe that the option for "on-demand" is quite frequent. On the other hand, it is uncommon the editorial choice of providing an overview of the data first or last.

We also observed that none of the 25 examples includes a *history*. The need for recording the process can be particularly important in the discovery of complex visualization. A history enhances the user experience through key actions, such as undo, replay, and the progressive refinement of the exploration [15].

C. Bumping into conceptual redundancies

The last set of conclusions derived from the analysis on what each novel tripartite technique actually means in the ST context. We found that, on a conceptual level, some actions may be potentially translated through more than one interaction technique. Most of these overlaps were found on the experience of *zooming* and *overview*.

As seen in Section III, *overview* can be decomposed in *overview-first*, *overview-last*, and *overview-on-demand*. This is frequently a narrative choice dependent on the author's intention. During our analysis, a great disparity in the interaction technique *overview* was encountered. We have found that in some visualizations, it is not reasonable to include it and in others the *overview* is implicit. In our sample, an *overview* not being suitable happens in case *m*. Here, the objective is to compare how the total number of commuters is distributed geographically at different times. A similar rationale is adopted in case *t*, where the results of the German elections from seven different years are contrasted. Hence, when the analysis is heavily centered on the relationships between time segments, we assume that an overview is illogical. In opposition, we found that in visualizations that are continuously evolutive by nature, an *overview-last* is implicit. In animations that wrap up the accumulation of all events, without any retraction or withdrawal of data while the animation is unfolding, we observe an overview at the last time point. This is the case of *p*, in which the world's urban settlements are incrementally plotted on the map and the case of *u*, where, in the end, it is possible to observe the total number of Airbnb reservations.

In Section III, we make the distinction between two interaction techniques that provide the possibility of switching from a dynamic dot density map to a network map, displaying the data in two alternative ways: *encode-space*, when every coordinate for all time points is represented, and *reconfigure-time*, when the first and last points are connected. Throughout the analysis we realized that, in both scenarios, the effect of bigger picture induces a feeling of distancing. Thus, simultaneously, these actions also give a bird's-eye view. Beyond that, concurrently, this interaction constitutes also a conceptual *zooming-time*.

Linking and *details-on-demand* actions can also be considered *zooming* interaction techniques. Ultimately, these allow a feeling of approximation to the theme, providing more information on the topic covered by the visualization. This phenomenon can be seen, for example, in cases *b* and *c* of the study, as observed in Figure 2. In these visualizations, further individual details on the flights, airplanes, or ships are granted through these actions.

The intention of zooming is conceptually present when the user may vary the granularity of the temporal scale, due to the abstract feeling of approximation to the data. This happens in case *x*, for instance, by enabling the user to present the data per hour, day, week and month. Here, *zooming-time* overlaps simultaneously with *reconfigure-time* and *filtering-time*, since the user is *de facto* rearranging the temporal structure and omitting all the remaining results.

D. A novel taxonomy for interaction in spatio-temporal ST visualization

The major conclusion that emerged early on in the study was that a generic interaction taxonomy cannot be applied to analyze ST visualizations without several adjustments. Therefore, in this paper, we present a new specialized taxonomy to study interaction in this context. The proposed classification scheme assumes the necessary structural ST triad framework, Theme, Time, and Space, as conceptual focus. The operational dynamic of the framework is robust because it broadly translates "the way in which humans view the world and the way we learn about it by gradually identifying meaningful patterns and recurrences of elements in space-time" [6].

As exhibited in Table III, we have divided the techniques into two categories. The first one introduces the total seven criteria that are in some way resulting or dependant on the properties of ST data. In its turn, the second category encompasses the generic criteria that are transversely relevant to other specific contexts. To provide a finer comprehension of its applicability, each technique is complemented by a short description.

V. Conclusions and Future Work

Interactivity and its inherent dynamic features provide a solid ground for the visualization of changes over time and space. The initial objective of this study was a deep understanding on how authors are taking advantage of interaction in the context of ST visualization. The attempt of adoption of a generic taxonomy for interaction in InfoVis unveiled that ST information has inherent specificities. A conversion of the generic taxonomy into a dedicated approach resulted in new specific criteria that consider the decomposition of most interaction techniques in Theme, Time, and Space, originating a specialized taxonomy.

This study lead to a comprehensive approach to how the different dimensions in ST visualization articulate, complement, or overlap each other. From the sample of 25 cases of reference, we could also analyze which interaction techniques are primarily included and which are lacking usage. We aim to contribute to a finer understanding of interactivity in ST visualization, expecting that these outcomes lead to better future decision-making in the design process and as ground knowledge for tools and frameworks to assess the maturity of interaction in this context.

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ST	1	filtering	*theme*	Display only items with the properties in which I am interested.
			time	Display only time points or intervals in which I am interested.
			space	Display only locations in which I am interested.
	2	selecting	*theme*	Mark or track items with the properties in which I am interested.
			time	Mark or track time points or intervals in which I am interested.
			space	Mark or track (a) location(s) in which I am interested.
	3a	zooming	*time*	Vary the level of abstraction on a time interval.
			space	Zoom in or out on an area.
	5	connect / relate	*theme*	Relate two or more items from different themes.
			time	Relate two or more time points or intervals.
			space	Relate two or more locations.
	6	reconfigure	*theme*	Give me a different arrangement of the data.
			time	Give me a different arrangement of the temporal structure.
			space	Give me a different arrangement of the locations.
	7	encode	*theme*	Give me a different visual code for the thematic components.
			time	Give me a different visual code for the temporal structure.
			space	Give me a different visual code for the geographical components.
	4	overview	*first*	Give me an overview of all the occurrences first.
			last	Give me an overview of all the occurrences last.
			on-demand	Give me an overview of all the occurrences anytime.
Generic	3b	details-on-demand	*theme*	Show me details on a specific item on demand.
	3c	linking	*theme*	Take me to complementary information.
	8	history	-	Allow me to retrace the steps I take in the exploration.
	9	extraction of features	*theme*	Allow me to extract data in which I am interested.
	10	participation / collaboration	*theme*	Allow to contribute with data.
	11	gamification	*theme*	Show me the data in a more playful way.

Table III: A novel interaction taxonomy for ST visualization

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