

Data and Task Characteristics in Design of Spatio-Temporal Data Visualization Tools

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Abstract

It is widely recognized that data visualization may be a powerful instrument for exploratory analysis. In order to fulfill this claim, visualization software must be carefully designed taking into account two principal aspects: characteristics of the data to be visualized and the exploratory tasks to be supported. The tasks that may potentially arise in data exploration are, in their turn, dependent on the data. Developers of visualization software need comprehensive and operational typologies of data and tasks, where the task typology has an explicit connection to possible data components and characteristics.

In the paper we present three examples of task-driven design of visualization software for different types of spatio-temporal data. We demonstrate that, first, different exploratory tasks may be anticipated in these three cases and, second, different sets of tools are required to properly support exploration of the data, although there are some common techniques and interface elements used in all applications. Prior to the description of the examples we briefly survey relevant typologies of data and tasks available in the literature.

Keywords: exploratory data analysis, spatio-temporal data, geographic visualization, interactive data displays, animated maps

1 Introduction

The large number of recently published papers and books combining in their titles the words “geography” and “time” or their derivatives indicates the importance of temporal issues for the contemporary geographic information science. It can be noted that most publications refer in this or that way to the same cardinal problem “How to make computers (or, more specifically, GIS) understand temporality and

handle time-related information?" Various formal theories have been suggested that attempt to simulate human's understanding of time and (spatio-)temporal reasoning (see, for example, Allen 1984, Galton 1987, Egenhofer and Al-Taha 1992, Cohn et al. 1998, Frank 1998). On this basis different frameworks and methods for internal representation and operation of spatio-temporal data in GIS are devised (Langran 1992, Peuquet 1994, Worboys 1998, Wachowicz 1999).

As developers of software tools for geographic data visualization in the sense defined in (MacEachren 1994, MacEachren and Kraak 1997), we focus primarily on another problem related to space, time, and computers: "How to make computers support a human analyst in visual exploration of spatio-temporal information?" While internal representation of spatio-temporal data is an important issue in implementation of tools, our main research interest is how the data should be displayed to a user.

Our work on developing visualization-based exploratory tools was initially actuated by practical needs: we participated in several projects where different types of spatio-temporal data had to be sensibly presented to users. We would certainly like to base our activities on a solid theoretical and/or methodological background. However, it appears that such a background is not readily available. Publications on visualization of spatio-temporal data mostly describe diverse techniques and systems implementing them (Kraak et al. 1997, Blok et al. 1999, Fredrikson et al. 1999, Harrower et al. 2000, Oberholzer and Hurni 2000, Slocum et al. 2000). A systematization effort has been only done for static ("paper") cartographic representations (Vasiliev 1997).

Our attention was first attracted to the technique of map animation that can be found in almost all software systems for visualization of spatio-temporal data. However, we found soon that this technique in its "pure" form (i.e. playing a sequence of "snapshots" representing states of a phenomenon at successive moments of time) does not work so well for arbitrary data as it does in demonstrating evident trends like urban growth (Tobler 1970). The main problem is that animation does not give an analyst an opportunity to compare directly states at different time moments. In order to detect and evaluate changes, she/he has to compare the state viewed at the current moment with mental images of earlier states. Investigation of temporal trends would require memorizing of a large number of consecutive states. Hence, comparison and trend detection must be supported by other techniques, possibly, combined with animation.

Our next observation was that there are no such techniques that would be applicable to or work equally good for all types of data. Design of an appropriate software tool must be based on careful consideration of two aspects: 1) what kind of data it is going to deal with and 2) what questions it must help answer. We see the required methodological basis for such a work as a linkage between possible types of spatio-temporal data, possible types of questions about these data, or analytical tasks, and techniques that could support finding answers to these questions. Since we failed to find a suitable methodology in literature, our work on tool development has been mostly empirical. In this paper we are going to present some of our results, specifically, three different tools each designed for a specific type of data. In description of each tool we explicitly state what analytical

tasks it has been meant to support. The main purpose of the paper is to demonstrate the impact of data characteristics on the tasks that can emerge in exploration of these data and, hence, on the requirements to the tools for supporting visual data analysis.

Prior to the description of the tools, we survey relevant typologies of spatio-temporal data and possible analytical tasks.

2 Typologies of Data and Tasks

Spatio-temporal data involve three major components: space (*where*), time (*when*), and objects (*what*) (Peuquet 1994). Each component consists of specific elements that may have some attributes and be linked by various relationships. Existing data typologies refer to these components. Thus, it is conventional to classify spatial objects and phenomena according to their spatial distributional form into discrete and continuous (MacEachren 1995). A continuous phenomenon is defined everywhere over the territory (e.g. population density or air temperature) whereas a discrete one occurs at distinct spatial locations or within restricted areas (e.g. deposits of resources). Discrete objects are usually further subdivided into point, line, and area objects. Non-spatial, or thematic, properties of spatial objects are expressed through attributes, the latter being most often classified according to the so-called “level of measurement” into nominal, ordinal, and numeric (Bertin 1967/1983). Sometimes numeric attributes are further subdivided into interval and ratio measurements.

Spatio-temporal phenomena are also classified according to their temporal properties, in particular, according to the type of changes that occur to them over time (Blok 2000):

- existential changes: appearing, disappearing, reviving of objects or/and relationships;
- changes of spatial properties of objects (location, size, shape);
- changes of thematic properties, i.e. values of attributes.

In existential changes further diversity is possible depending on whether the duration of events is significant or not. An analyst may treat events (e.g. earthquakes) as instant when duration of an event is negligibly short in comparison to the length of the time interval under analysis or when it is only important for the analysis when an event appears but not how long it lasts. Sometimes only one type of changes takes place or is of interest for an analyst, but in many cases one needs to consider several types simultaneously.

According to the three components comprising spatio-temporal data, Peuquet (1994) defines three basic types of possible questions about such data:

- *when + where* → *what*: Describe the objects or set of objects that are present at a given location or set of locations at a given time or set of times.

- *when + what* → *where*: Describe the location or set of locations occupied by a given object or set of objects at a given time or set of times.
- *where + what* → *when*: Describe the times or set of times that a given object or set of objects occupied a given location or set of locations.

This classification parallels the notion of *question types* introduced by Bertin: “There are as many types of questions as components in the information” (Bertin 1967/1983, p.10). A complementary division of questions proposed by Bertin is according to so-called *levels of reading*: elementary, intermediate, and overall. Elementary questions refer to individual elements of data (e.g. individual places, time moments, and objects) while questions of the intermediate and overall levels address more general characteristics of a phenomenon, e.g. how it is distributed in space, how it behaves in time, or how characteristics are distributed over a set of objects. To our impression, there is no principal difference between the intermediate and overall levels, as defined by Bertin. Both levels involve consideration of sets rather than individual elements. The difference is whether the whole set or its subsets are considered.

It should be noted that Bertin considered data in general, not specifically spatio-temporal data. Koussoulakou and Kraak (1992) demonstrate that in the specific case of spatio-temporal data the distinction according to the reading levels can be independently applied to the spatial and to the temporal dimensions of the data. For example, the question “What is the trend of changing values at location *l*?” belongs to the elementary level in relation to the spatial component and to the overall level with respect to the temporal component. An analogous observation can be also made for the object dimension.

Hence, each of the Peuquet’s general question schemes of the form $A+B \rightarrow X$ (where *A* and *B* denote known, or given, data components and *X* stands for unknown information) can be further subdivided according to the level on which the known information is specified: elementary *A* and *B*, elementary *A* and overall/intermediate *B*, overall/intermediate *A* and elementary *B*, and overall/intermediate *A* and *B*.

It should be further borne in mind that any general scheme may acquire different shades of meaning when being applied to different types of spatio-temporal data. For example, one possible type of spatio-temporal data is data about movement of discrete objects. In relation to such data the three basic types of questions could be formulated as follows (for simplicity, we consider only the elementary level):

- *when + where* → *what*: What objects were present at the time *t* at the location *l*?
- *when + what* → *where*: What was the location of the object *o* at the time *t*?
- *where + what* → *when*: When did the object *o* visit the location *l*?

Another type of spatio-temporal data is changing attribute data referring to static spatial objects or locations, such as data about changes in population number and structure by municipalities of a country. Possible questions about this type of data are:

- *when + where* → *what*: What was the value of the given attribute at the time t at the location l ?
- *when + what* → *where*: At what locations was the value v of the attribute attained at the time t ?
- *where + what* → *when*: When did the value v of the attribute attained at the location l ?

It seems strange to us that none of the existing typologies of possible questions pays any special attention to tasks of comparison, for example, how did the position of object o change from the moment t_1 to the moment t_2 ? How does the attribute value at the location l_1 (at the time t) differ from that at the location l_2 ? From our experience we know that comparison tasks often require special tools to support them, and therefore it is important to distinguish them from the type of tasks discussed above (let us call them “inquiry” tasks).

In the remaining part of the paper we are going to demonstrate on a few specific examples of different spatio-temporal data how a designer analyses data characteristics in order to determine possible types of questions that may arise and how this guides the choice of appropriate exploratory techniques to suggest to the users.

3 Time Controls and Dynamic Map Display

Despite of the variety of spatio-temporal data, there are some general techniques applicable to all data types. Specifically, the spatial aspect of data is typically visualized with the use of maps, as they are well suited for conveying spatial information to human’s eye. Therefore all our exploratory tools involve interactive map displays. For dealing with the temporal dimension of data, we have developed an assembly of interactive widgets further referred to as *time manager* (see Figure 1). The time manager is connected to a map display. The user may choose what is represented in the map:

- *instant view*: the map represents the state of the world at a selected moment;
- *interval view*: the summary of events, movements, etc. that occurred during a selected interval.

For selecting an interval, the user specifies its starting moment and length. To select a moment, the length of the interval should be set to one time unit.

The current display moment or interval can be shifted forth and back along the time axis either by pressing the buttons “step forth” (“>”) and “step back” (“<”) or by dragging the time slider (at the top of the time manager window). Each action causes the map being immediately redrawn to represent the new moment or interval. This kind of operation may be called *user-controlled animation*. It is also possible to run an *automatic animation* (by pressing the buttons “>>” or “>>...”). In this mode the tool iteratively shifts the current moment/interval by the specified

number of time units (step). The user may control the speed of the automatic animation by varying the parameter “delay”.

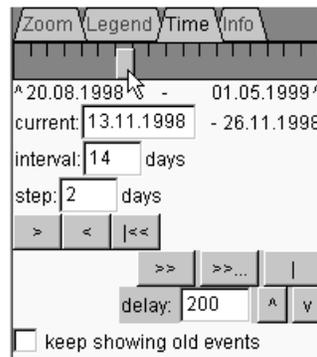


Fig. 1. Time manager

While the time controls and the dynamic map display are common for all types of spatio-temporal data, the content of the map and the visualization methods used vary depending on the data type. For some data types the dynamic map is combined with other exploratory tools, as will be shown below.

4 Visualization of Instant Events

Within the project “Naturdetektive” (see the URL <http://www.naturdetektive.de>) schoolchildren from all over Germany registered through the Internet their observations of nature, specifically, when and where they have noticed certain plant or bird. For some plants the children had to distinguish different stages of development: appearance of first leaves, beginning of blossoming, or appearance of fruits. Our task in the project was to design and implement such visualization of the collected data that could be used, on the one hand, in schools for educational purposes, on the other hand, by project managers and interested public to examine children’s involvement in the project.

The observation data can be treated as instant events. The events differ in their qualitative characteristics: the species observed and, possibly, the stage of its development. Taking into account the peculiarities of the data, we anticipated the following types of questions:

- Elementary level (with respect to time):
 - What species and in which states were observed at the moment t around the location l / in the area a ? What species and states were predominantly observed over the whole territory at the moment t ? Are there any differences in the variety of species observed on the north and on the south? etc.
 - Where was the species s (in the state s') observed at the moment t ? What was the spatial distribution of observations of the species s at the moment t ?

- When was the species s (in the state s') observed around the location l / in the area a ? When did the largest number of observations of the species s occur?
- What are attributes of a particular observation, e.g. who made it, when, in what environment, etc.?
- Intermediate/overall level (with respect to time):
 - How did the variety of species observed at the location l / in the area a / over the whole territory change over time?
 - How did the occurrences of the species s (in the state s') at the location l / in the area a vary over the time? How did the spatial distribution of observations of the species s change over the time?
 - What is the spatio-temporal behavior of the species s (i.e. when does it/ its different stages appear in different parts of Germany, how long are the intervals between appearing of different stages, etc.)?

From the analysis of the possible questions we saw first of all the necessity of visual discrimination of observations of different species. Therefore we have chosen to visualize the data on the map using iconic symbols with the shapes resembling the appearance of the species (Figure 2). Variation of icon colors was used for representing different stages of plant development.

Furthermore, seeking answers to the questions requires the following operations:

- Selection of specific time moments (supported by the time manager).
- Focusing on particular locations or areas (supported by map zooming and panning facilities).
- Selection of a particular species. For this purpose we implemented a “species toolbar” in which the users can either choose one of the species (in this case the icons of the other species are hidden) or all the species at once. The second mode allows the users to study the total variety of species and its development over time.
- Access to information about a particular observation. To support this operation, we implemented a lookup interface that requires the user just to point with the mouse at the corresponding icon. All the information about this observation (date, species, state of development, and who made the observation) will be shown in a popup window (see Figure 2). An observation record may have a reference to a URL where additional information about the species or/and the observer is given. This URL is opened when the user clicks on the icon.
- Observing changes over time. This operation is done using map animation controlled through the time manager. The animation allows the user to investigate, on the one hand, evolution of the variety of species or the spatio-temporal behavior of a particular species, on the other hand, how participation of the schoolchildren in the project developed over time.

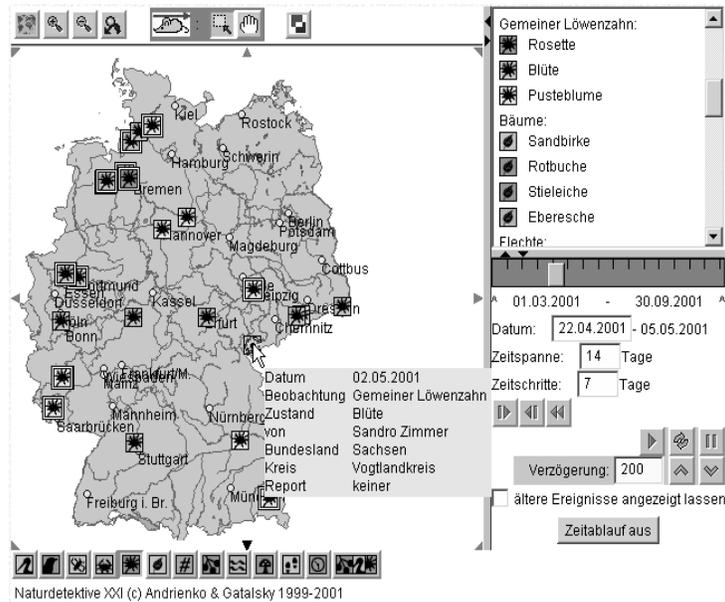


Fig. 2. Visualization of nature observations

Although the resulting tool supports sufficiently well comparisons of different areas and distributions of observations of different species, it does not support comparison of different time moments. For the latter purpose one could suggest using two (or even more) parallel map displays. Another opportunity is to represent “older” events on the map in a specific way, for example, by “dimmed” icons. However, in this particular case we preferred to avoid further complication of the tool since it was intended to be used by children.

Another example of instant events is occurrences of earthquakes. For this kind of data we used circles to represent on the map locations of earthquake epicenters. The earthquakes were characterized by different numeric attributes, such as magnitude, depth, intensity, or radius. We gave the users an opportunity to select one of the attributes at a time for representation on the map and encoded attribute values by variation of degrees of darkness: darker shades corresponded to higher values of the represented attribute, and lighter – to lower. Interested readers can run the applet showing data about earthquakes in Europe in 1980-1983 at the URL <http://www.ais.fhg.de/and/java/show1field/eq.html>.

A useful addition to the described tools for exploration of instant events would be calculation and visual representation of various statistics: the total number of events that occurred at each moment/interval, the number of events of each kind (e.g. observations of each species), the average characteristics of events (in a case of numeric data), etc.

5 Visualization of Object Movement

The most important types of questions that could be expected to arise in investigating movement of objects in space are following:

- Where was each object at a selected moment t ?
- When did a particular object o visit the location l ?
- How long did it stay at this location?
- How did the positions of objects change from moment t_1 to moment t_2 ?
- What were the trajectories of the objects during the interval $[t_1, t_2]$?
- What was the speed of movement during the interval $[t_1, t_2]$?
- How did the speed of movement change over time or with respect to spatial position?

An example of data about moving objects is telemetric observations of migration of white storks to Africa in autumn and back to Europe in spring. For these data we chose directed line segments (vectors) as representation of changes of object positions between successive moments of measurement. A sequence of vectors shows the trajectory made by an object during a time interval. The user can view the trajectory of each bird separately or trajectories of several birds simultaneously. It is possible to see and compare the whole trajectories made during the whole time span under analysis as well as fragments of the trajectories made during a selected interval.

In our tests we found especially interesting and useful a dynamic interval view, i.e. a combination of the interval view (as defined in Section 2) with the automated animation. The interval view for this kind of data shows route fragments made by the objects during a selected interval. In the course of the animation (see Figure 3) the vector chains look like worms crawling on the map. It is not merely fascinating; these “worms” reveal important dynamic characteristics of movement. The length of a “worm” shows the speed of movement. Shrinkage of the “worm” signalizes that the movement of the object slows down, and expansion of the “worm” means that the movement becomes faster. When an object stops its movement and stays for some time in the same place, the corresponding “worm” reduces to one dot. It would be practically impossible to do such observations using an ordinary animated presentation showing just positions of the objects at successive moments of time.

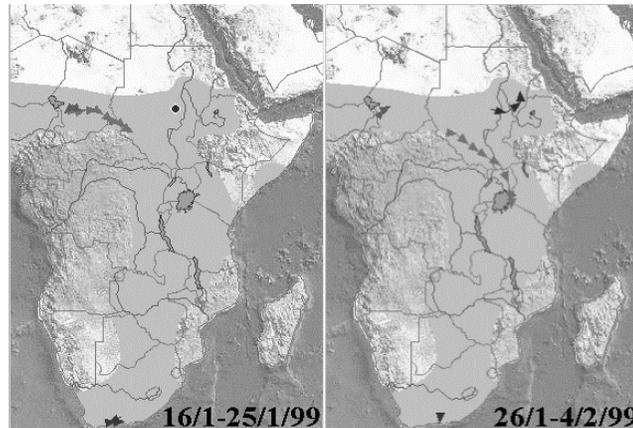


Fig. 3. Different behaviors of white storks in Africa

We invite the readers to explore the movement of the storks by running the Java applet that is available in the WWW at <http://www.ais.fhg.de/and/java/birds/>. A more detailed description and color illustrations can be found in (Andrienko et al. 2000).

A useful enhancement of this visualization method would be a tool to synchronize presentation of movements made during different time intervals. This would allow an analyst to detect similarities in asynchronous behaviors and periodicity in movements. It would be also appropriate to calculate for each object and represent to the analyst the distance traveled during a selected interval or from the beginning of the observation to the current display moment. A graph showing dependence of the traveled distance on the time passed could help in studying variation of the speed of movement and comparison of speeds of different objects.

6 Visualization of Changing Thematic Data

In this section we describe the tools we developed for visualization of time variation of thematic data associated with spatial objects, more specifically, values of a numeric attribute referring to areas of territory division. Examples of such data are demographic or economic indices referring to units of administrative division of a territory. By their nature, the data correspond to a continuous spatial phenomenon but have been discretized by means of dividing the territory into pieces. In contrast to events or moving objects, these pieces can be considered as stable objects that typically do not disappear and do not change their location.

In the two applications described above it was possible to show data for several different time moments on a single map. This created good opportunities for comparisons, detecting changes, and estimating the degrees of changes. With the data discussed in this section such combination is rather difficult since at each moment the objects cover the whole territory. A possible technique is putting on

the map bar charts where height of each bar is proportional to the value of the attribute at some time moment. This technique, however, is only suitable for finding answers to elementary questions, i.e. estimating changes of attribute values at a particular location. It is impossible to observe changes in spatial distribution of attribute values, or to locate places where the most significant changes occurred, or to perform other tasks requiring an overall view on the whole territory.

The overall view is well supported by the cartographic presentation method called choropleth map. According to this method, the contour of each geographic object is filled with some color, the intensity of which encodes the magnitude of the value of the attribute. We combined this representation method with time controls and received a dynamic choropleth map display (Figure 4, center and right). This display provides a good overall view of the spatial distribution of attribute values at a selected time moment and dynamically changes when another moment is chosen, in particular, in the course of animation.

However, the choropleth map is poorly suited for the tasks of estimating changes and trends occurring in each particular area and is even less appropriate for comparing changes and trends occurring in different areas. Therefore we found it necessary to complement the dynamic map with an additional non-cartographic display, *time plot*, showing the temporal variation of attribute values for each area (see at the bottom of Figure 4). The X-axis of the plot represents the time, and the Y-axis – the value range of the attribute. The lines connect positions corresponding to values of the attribute for the same area at successive time moments. Like a map with bar charts, the time plot is good for examining dynamics of values for each individual object. Besides, it supports much better than a chart map comparison of value variations for two or more objects and detecting objects with outstanding behavior. It should be noted that we were not the first who combined a map with a time plot; such a combination may be found, in particular, in the famous Minard's presentation of Napoleon's campaign in Russia (described, for example, in Tufte 1983).

In our implementation the time plot is an active display sensitive to mouse movement: it highlights the line or bundle of lines pointed on with the mouse. Simultaneously, the corresponding objects are highlighted in the map. The link works also in the opposite direction: pointing on any object in the map results in the corresponding line being highlighted in the time plot. So, the map serves as a "visual index" to the plot making it easy for the user to focus on any particular object for considering dynamics of its characteristics with the use of the plot. And vice versa, it is easy to determine which object corresponds to any particular behavior that attracted the analyst's attention.

However, even being enhanced with the time plot, the map display still does not support well enough comparison of different moments and observation of changes on the overall level. To support such analytical tasks, we have devised a number of data transformation techniques supporting comparison of the values for each moment:

- with the values for the previous time moment,

- with the values for a selected fixed moment,
- with the value for a selected object,
- with a constant reference value.

The interactive controls for visual comparison can be seen on the left of Figure 4.

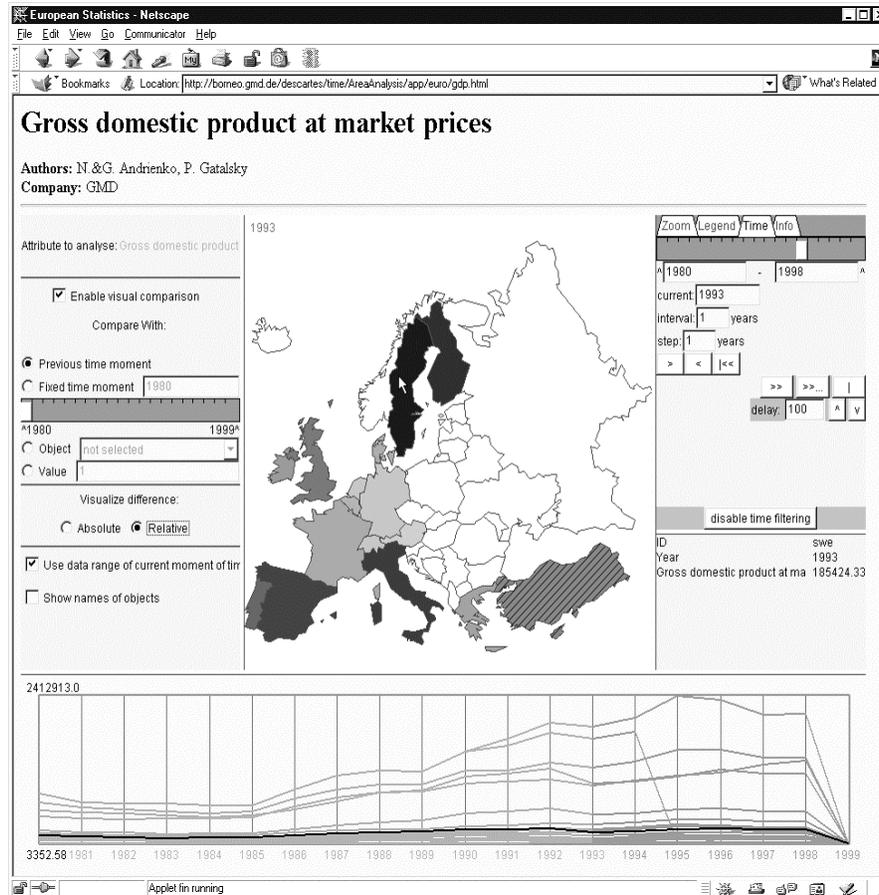


Fig. 4. Analysis of change of the gross domestic product in European countries. The map shows relative differences between the years 1993 and 1992. For the black-and-white reproduction we applied hatching in order to distinguish the country where the GDP decreased (Turkey) from the countries where it increased. In the original screenshot decrease and increase were manifested by blue and brown colors, respectively.

In the comparison mode the map represents transformed data (computed absolute or relative differences between values) rather than the initial attribute values. The results of computations are shown using the bi-directional color scheme (Brewer 1994): shades of two different colors represent values higher and lower than the current reference value. We have chosen to use shades of brown

and blue, respectively. The degree of darkness shows the amount of difference between the represented value and the reference value. White coloring is used for objects with values exactly equal to the reference value.

The concept of the reference value has different meanings depending on the comparison operation selected. In the comparison with the previous time moment the reference value for each object is the value of the attribute for the same object at the previous moment. So, it is easy to distinguish visually the areas with growth of values from those where the values decreased. In a similar way comparison with a fixed moment is done; the reference values in this case do not change with the change of the currently displayed time moment. When comparison with a selected object is chosen, the reference value for all the objects is the value for the selected object at the current moment, i.e. it is the same for all objects. The user sees which objects have lower values than this object, and which higher. When the currently represented time moment changes, the new reference value comes into play, unlike the case with a constant reference value that may be only explicitly changed by the user.

Visualization of differences can be combined with animation. On each step of the animation the differences are recalculated and shown in the map.

In encoding time-variant data by degrees of darkness there are two possible approaches. We can assign the maximum degree of darkness to the maximum attribute value in the whole data set or to the maximum of the subset of data referring to the currently represented time moment. Each approach has its advantages: the first allows consistent interpretation of colors in successive images while the second shows more expressively value distribution at each time moment and makes changes in the distribution more noticeable. Therefore we have implemented both approaches, and the user can switch from one of them to the other.

As the user chooses the comparison mode and applies various variants of comparison, the time plot changes in accord with the map. Initially the time plot shows the source data, i.e. values of the explored attribute at each time moment. In the comparison mode it switches to displaying the results of subtraction of the reference values from the source values (absolute difference) or division of source values by the reference values (relative difference).

In Figure 4 one can see a screenshot demonstrating the suggested facilities for exploration of time-variant numeric data. The map represents amounts of the gross domestic product by European countries in 1993 in comparison with the previous year, 1992. Since shades of blue and brown are not distinguished in a grayscale reproduction, we have artificially marked the only country colored in blue (specifically, Turkey) with hatching. The applet with the data is available at the URL <http://www.ais.fhg.de/and/time/AreaAnalysis/app/euro/gdp.html>.

We continue to develop the tool described. In particular, we implement temporal aggregation of numeric attribute data. The system will calculate and visualize summary statistics of data on the shown interval: average, minimum, maximum values, etc. In the comparison mode, the aggregation will be applied to the calculated values.

7 Conclusion

Visual exploration of spatio-temporal data requires tools that could help find answers to different types of questions that may arise in relation to such data. In this paper we have shown that the questions an analyst is likely to be concerned with are greatly related to the characteristics of data under analysis. Therefore different sets of exploratory techniques are needed for different types of spatio-temporal data. We have considered three different types of data: instant events, object movement, and changing thematic characteristics of static spatial objects. We have described how we designed visualization tools to support exploratory analysis of each type of data. Thus, in analysis of movement especially productive is combination of map animation with an interval view showing the trajectories of objects made during intervals. Various ways of data transformation and combination of a dynamic map display with a time-series plot are useful for analysis of thematic data associated with area objects. The time plot can be also recommended for representing calculated statistics for other types of spatio-temporal data, such as numbers of events or traveled distances.

The types of data we considered in the paper do not cover all possible variety of spatio-temporal data. It was also not our intention to enumerate all possible techniques that can support exploration of each type of data. The main objective was to demonstrate that development of interactive visualization tools must be data- and task-driven. It should be noted, however, that currently there is no appropriate theoretical and methodological background for such work, and it needs to be built.

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