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Exploratory spatio-temporal visualization: an analytical review

Natalia Andrienko*, Gennady Andrienko, Peter Gatalsky

Fraunhofer AIS, Institute for Autonomous Intelligent Systems, SPADE, Spatial Decision Support Team, Schloss Birlinghoven, Sankt-Augustin, D-53754 Germany

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Abstract

Current software tools for visualization of spatio-temporal data, on the one hand, utilize the opportunities provided by modern computer technologies, on the other hand, incorporate the legacy from the conventional cartography. We have considered existing visualization-based techniques for exploratory analysis of spatio-temporal data from two perspectives: (1) what types of spatio-temporal data they are applicable to; (2) what exploratory tasks they can potentially support.

The technique investigation has been based on an operational typology of spatio-temporal data and analytical tasks we specially devised for this purpose. The result of the study is a structured inventory of existing exploratory techniques related to the types of data and tasks they are appropriate for. This result is potentially helpful for data analysts—users of geovisualization tools: it provides guidelines for selection of proper exploratory techniques depending on the characteristics of data to analyze and the goals of analysis. At the same time the inventory as well as the suggested typology of tasks could be useful for tool designers and developers of various domain-specific geovisualization applications. The designers can, on the one hand, see what task types are insufficiently supported by the existing tools and direct their creative activities towards filling the gaps, on the other hand, use the techniques described as basic elements for building new, more sophisticated ones. The application developers can, on the one hand, use the task and data typology in the analysis of potential user needs, on the other hand, appropriately select and combine existing tools in order to satisfy these needs.

*Corresponding author. Tel.: +49-2241-142329, +49-2241-142486; fax: +49-2241-142072.
E-mail addresses: natalia.andrienko@ais.fraunhofer.de (N. Andrienko), gatalsky@ais.fhg.de (P. Gatalsky).
URL: http://www.ais.fraunhofer.de/SPADE.

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1. Introduction

Modern computer technologies provide better than ever before opportunities for storage, management, visualization, and analysis of dynamic, i.e. temporally variable, data, including dynamic spatial data (further referred to as spatio-temporal data). Researchers in geography and cartography actively try to utilize these opportunities in designing new techniques and developing software tools to support visual exploratory analysis of spatio-temporal data. This paper offers a survey of such techniques and tools made on the basis of examination of the currently existing literature.

The goal of the paper is similar to that of the review by Vasiliev [1] who systematized the existing methods for representing spatio-temporal information in traditional maps. The resulting catalogue provides guidelines for selection of appropriate cartographic symbology depending on the data to be mapped. Moreover, it can serve as a basis for the design of new, more sophisticated graphical representational forms. We strive at creating a similar catalogue for modern, computer-based techniques. However, this is not the only difference of our work from that of Vasiliev. Vasiliev surveyed the traditional cartographical methods from the perspective of communication, i.e. delivery of a desired message to expected map readers, whereas we take the perspective of data exploration, i.e. using the techniques for revealing new, previously unknown information about spatio-temporal phenomena. In other words, our research refers to the "visualization" corner of the (Cartography)^3 suggested by MacEachren [2], which is opposite to the "communication" corner corresponding to Vasiliev's study.

In accord with this exploratory perspective, we classify and evaluate the techniques and tools from the perspective of, first, the characteristics of the spatio-temporal data they are applicable to, second, the types of exploratory tasks they can potentially support, or, in other words, questions about data they can help answer. We prefer this classification scheme to others (briefly considered below) because it is more suitable as a basis for selection of appropriate analysis tools depending on data to analyze and the goals of analysis. Of course, this classification cannot be directly proposed to end-users of visualization tools. However, there are a few indirect ways of its utilization for the ultimate benefit of the end-users. Thus, it can help developers of various domain-specific applications to appropriately select and combine available visualization tools in order to satisfy user's needs. Another possibility is to incorporate the suggested classification in an expert system advising the end-users which techniques to employ in what situations. Furthermore, we hope that the classification could serve as a basis for conscious design of visualization tools for spatio-temporal data. We believe that explicit consideration of possible analysis tasks could prompt tool designers and developers to improve the existing tools and to address the insufficiently supported task types in the design of new tools.

Other classification schemes for visualization techniques have been proposed, for example, by Cleveland [3], Buja et al. [4], Hinneburg et al. [5], and Gahegan [6]. Cleveland considers visualization techniques from the perspective of the number of data components (variables) to be simultaneously analyzed and distinguishes techniques for univariate, bivariate, trivariate, and hypervariate data. Temporal variation is only considered as a special case of bivariate data. Buja, Cook, and Swayne classify visualization tools into three broad categories: focusing individual views, linking multiple views and arranging views. These categories approximately correspond to three principal tasks the authors distinguish in data exploration: finding Gestalt, posing queries and making comparisons. The scheme suggested by Hinneburg, Keim, and Wawryniuk and further extended by Gahegan classifies exploratory visual techniques according to their method of construction and visual properties. This results in such categories as chart-based techniques, projection techniques, pixel techniques, iconographic techniques, etc. Additionally, Gahegan differentiates the techniques according to the supported style of user interaction. While each of these classification frameworks offers a useful perspective for viewing the variety of visualization tools, none of them corresponds to the goals of our review.

The set of techniques considered in the paper results from our search in the existing literature and in the Web as well as from our own experience in developing software tools for geographical visualization. It includes only the tools and techniques explicitly suggested for exploration of spatio-temporal data. While this set is sufficient for illustrating our ideas, we cannot guarantee its completeness. In describing the techniques we often refer to certain software systems (mostly research prototypes) where this or that technique is implemented. This may help interested readers in finding additional information about the techniques they would like to learn more about. In the appendix we enumerate the systems mentioned throughout the paper, specify the corresponding information sources and list the available techniques that were considered in the paper. However, we did not intend to make a full list of all existing software systems related to visualization or analysis of spatio-temporal data. It was also not our goal to evaluate the systems from the perspective of their functionality, usability, efficiency, etc., or to describe all techniques and functions available in them, or to compare peculiarities of implementation of this or that technique in different systems. On the opposite, we strived to regard the techniques in general, irrespective of their particular implementations in different systems.

The reminder of the paper is organized as follows. In the next section we describe our classification framework, i.e. the typology of spatio-temporal data and exploratory tasks we are going to use. After that we consider various types of data and tasks and enumerate the techniques being, to our opinion, appropriate for such data and tasks. At the end of each section we propose a summary of the exploratory techniques arranged according to the data and task types they address. We hope that this synopsis will be helpful both for developers of geovisualization tools and for data analysts by providing guidelines for selection of appropriate techniques for exploratory data analysis.

2. Spatio-temporal data and analytical tasks

There exists abundant literature discussing spatio-temporal data. Many researchers are primarily concerned with the issues of storage and management of time-referenced geographic data in geographic information systems (GIS) [7–10]. However, in our review we are not going to discuss different approaches to internal data representation or compare software packages according to the representational frameworks they incorporate. Instead we focus more on the nature and inherent properties of spatio-temporal data.

Appropriate concepts can be found, for example, in Blok [11]. We have adapted them for classification of spatio-temporal data according to the kind of changes occurring over time:

1. Existential changes, i.e. appearance and disappearance.
2. Changes of spatial properties: location, shape or/and size, orientation, altitude, height, gradient and volume.
3. Changes of thematic properties expressed through values of attributes: qualitative changes and changes of ordinal or numeric characteristics (increase and decrease).

In the paper we shall use the term "events" to denote spatial objects undergoing existential changes. We distinguish momentary and durable events. The first category includes events the duration of which is very small in comparison to the time period under analysis or not relevant for the analysis, for example, duration of an earthquake in studying dynamics of earthquake occurrences over a year.

We have also looked in the literature for an appropriate typology of data exploration tasks. We have found that task typologies suggested in the areas of visualization and human–computer interaction are rather numerous. In order to understand better their differences and to select the most appropriate one, we have made an attempt to classify the typologies. We have considered them from the perspective of a generalized view of the process of data analysis adapted from Qian et al. [12]. Initially an analyst has some *information need*. This need can be described by stating what is known (given) and what is to be found. In order to find the needed information, the analyst plans a sequence of *operations* to be applied to the data. Finally, she/he tries to perform these operations using available *tools*. Different approaches to defining possible tasks refer to different stages of the data analysis process. Thus, there are typologies that define tasks mostly as abstractions of existing GIS tools or visualization techniques [13,14]. Among the typologies related more to the intermediate stage some may be characterized as user-centered, i.e. defining possible tasks in terms of cognitive operations performed by a user, for example, "locate", "identify", "distinguish", etc. [15–17]. Other researchers [12] define the tasks as operations with sets: "union", "intersection", "selection", etc.

For the purposes of our research we needed a typology referring more to the initial stage of data analysis and encompassing potential information needs (questions) of an analyst. A classification of this kind is suggested, for example, by Roth and Mattis [18]. In contrast to this and similar classifications, which just enumerate certain task types without presenting a sufficient rationale for the selection of these particular categories, Bertin [19] takes a more systematic approach. In defining the potential information needs, he proceeds from the structure of data to be analyzed. Bertin's framework is based on two notions: "question types" and "reading levels". The notion of question types refers to components (variables) present in data: "There are as many types of questions as components in the information" [19, p. 10]. For example, a data set with stock prices by days contains two components, date and price. Respectively, two types of questions are possible:

- On a given date what is the price of stock X?
- For a given price, on what date(s) was it attained?

For each question type, according to Bertin, there are three *levels of reading*, elementary, intermediate and overall. The level of reading indicates whether a question refers to a single data element, to a group of elements or to the whole phenomenon characterized by all elements together.

While Bertin introduces his typology for arbitrary data, Peuquet [8] specifically considers spatio-temporal data. She distinguishes three components in such data: space (*where*), time (*when*) and objects (*what*). Accordingly, three basic kinds of questions are possible:

- *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.

The similarity of this typology to the Bertin's notion of question types is obvious. It can be noted that the notion of reading levels is also implicitly involved. Thus, questions addressing individual objects, locations and times correspond to Bertin's elementary reading level while questions about sets refer to the intermediate and overall levels.

Koussoulakou and Kraak [20] demonstrate that the notion of reading levels can be independently applied to the spatial and to the temporal dimensions of spatio-temporal 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.

The advantage of the task typology suggested by Bertin (and its spatio-temporal specialization by Peuquet) is that it directly relates tasks to components of data. Such a feature is very convenient for a tool or application developer: having a particular data set, she or he can easily anticipate the questions that may potentially arise and care about appropriate support for finding answers to them. Still, Bertin's scheme does not completely satisfy our needs. Thus, within the same question type and reading level an analyst may need to examine a single element (set) or to compare or relate two or more elements (sets). Bertin does not propose any notion to reflect this difference while we regard it as rather significant.

A distinction between exploratory tasks on identification and comparison is used by Blok [11] as one of two orthogonal dimensions for differentiating questions that may arise in monitoring spatio-temporal changes. "Comparison" is treated in a broader sense than just discovering similarities and differences. It includes also detecting relationships between processes, in particular, cause–effect relationships. The second dimension considered by Blok is the length of the time series to be analyzed. Thus, questions about trends (identification) or cause–effect relationships (comparison) can only be answered when sufficiently long time series are available. In our opinion, this dimension roughly parallels the notion of the reading levels.

We find it appropriate to extend the classification scheme of Bertin by adding the "identification–comparison" dimension, where the term "comparison" is used in the sense of determining relationships, in particular (but not exclusively), similarity–difference relationships. The distinction between identification and comparison applies to each question type, in terms of the search target. For example, two types of comparison tasks correspond to the question formula *when* + *where* → *what* introduced by Peuquet:

- Compare/relate the objects or set of objects present at locations l_1 and l_2 or sets of locations L_1 and L_2 at a given time or set of times.
- Compare/relate the objects or set of objects present at a given location or set of locations at times t_1 and t_2 or sets of times T_1 and T_2.

Analogously, two different comparison questions exist for each of the other two categories, *when* + *what* → *where* and *where* + *what* → *when*. If, in addition, we explicitly include the distinction between reading levels, the classification scheme becomes rather cumbersome.

For the purposes of our study, we found it possible to simplify somewhat the scheme without removing any of the classification dimensions, only by means of reducing the number of categories in each dimension. Thus, taking time as the focus of our attention, we reduced the distinction according to the search target just to two relevant categories:

1. Time is given while other types of information (objects, locations, properties, relationships) need to be discovered and described. We shall schematically designate this type of tasks as *when* → *where* + *what*.
2. Time needs to be discovered for given information of other types. This type of tasks will be further designated as *where* + *what* → *when*.

Each of these two categories includes tasks of identification and tasks of comparison (i.e. determining relationships), which, in turn, are differentiated according to the reading levels. In this paper we prefer to use the term "search levels" rather than "reading levels" due to our focus on exploration rather than communication of information.

The number of categories related to the concept "search level" can be reduced by means of uniting the intermediate and overall levels into a single category. In contrast to the elementary reading level, which deals with individual elements (time moments, locations or objects), this joint category involves consideration of sets and therefore can be called "set level" or "general level". The possibility of such unification is supported by our observation that exploration of a subset (intermediate search level) usually does not radically differ from studying a whole set (overall search level). Normally, the same techniques are applicable to both levels.

We would like to stress that the term "general search level" does not mean just a sequence of elementary tasks. Let us consider, for example, the following two questions addressing one and the same set of time moments:

1. What was the air temperature at this location on each day of the week?
2. What was the trend of the air temperature at this location over the week?

The first question addresses each time moment individually. It can be easily replaced by seven uniform questions concerning every day of the week. The second question cannot be decomposed in a similar way. It asks about an integral characteristic pertaining to the set as a whole. Hence, the first question must be ascribed to the elementary search level, despite of seemingly referring to a set, whereas the second question genuinely belongs to the general search level.

The resulting task typology is schematically shown in Fig. 1. We have somewhat simplified the picture for making it drawable. There is one dimension in the figure for the concept of the search level whereas, according to Koussoulakou and Kraak [20], this concept is independently applicable to the spatial and temporal components of data. Hence, the dimension "search level" in our cube stands for at least two dimensions as defined by Koussoulakou and Kraak. Moreover, if we apply the concept of search level to the three data components distinguished in the "*when*, *where*, *what*" framework of Peuquet [8], we shall get a three-dimensional classification space only for the possible combinations of search levels, and the entire classification scheme will thus become five-dimensional.

However, in accord with our focusing on the temporal component of spatio-temporal data, it is appropriate to treat the distinction according to the search level in the same way as we did for the search target. Specifically, we divide data components into "*when*", on the one hand, and "*what* + *where*", on the other hand, and crossbreed this division with the division into two search levels. This results in four categories:

- elementary "*when*" and elementary "*what* + *where*": describe characteristics of this object (location) at the given time moment;
- elementary "*when*" and general "*what* + *where*": describe the situation at the given time moment;
- general "*when*" and elementary "*what* + *where*": describe the dynamics of characteristics of this object (at this location) over time;
- general "*when*" and general "*what* + *where*": describe the evolution of the overall situation over time.

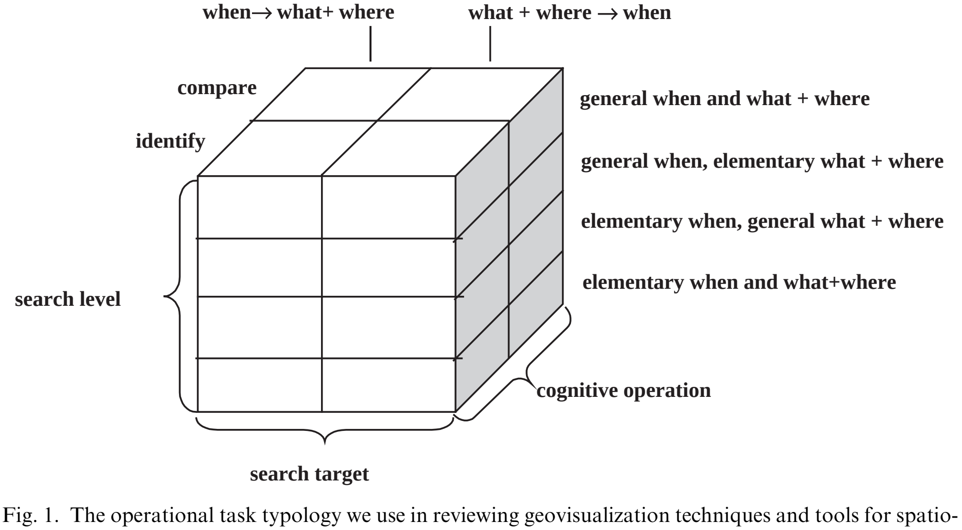

Fig. 1. The operational task typology we use in reviewing geovisualization techniques and tools for spatio-temporal data.

In our graphical representation of the entire task typology (Fig. 1) these four categories are shown along one dimension, although one may also view this scheme as a four-dimensional cube.

In the next section we relate existing exploratory techniques to types of spatio-temporal data while in Section 4 we consider these techniques from the perspective of the types of tasks they can support.

3. Exploratory techniques and data characteristics

3.1. Techniques applicable to all types of data

In comparison to paper maps, computer-based visualization tools have two principally new properties: interactivity and dynamics. These features enable two fundamental exploratory techniques that can be applied to various types of spatio-temporal data: querying and map animation.

3.1.1. Querying

Querying presumes that a software program is capable of answering users' questions concerning data under analysis. The questions (queries) include two major parts: the target and constraints. For example, the user may ask the program to retrieve all time moments when a specific object or attribute value was observed at a particular location. Here time is the target whereas constraints are the object or attribute value and the location. A query tool may not only provide access to source data but also compute various counts and statistical indices.

There are two principal ways in which a software tool can answer questions about data: (1) to provide the requested information in addition to what is already present on the screen; (2) to remove from the user's view the data that do not satisfy the query constraints. The former type of querying may be called "lookup" and the latter "filtering". Query tools may also differ in how the questions are stated. One option is to use some formal (machine-readable) language, but this is obviously inconvenient for end-users. Visual query languages [21] replace typing formal expressions by operating icons and menus. A visual language for querying spatio-temporal data is implemented, for example, in the system SpaTemp [22].

In many existing software packages the users may set queries by direct manipulation of various graphical elements on the screen. Thus, with the "dynamic query" tool [23], query constraints in terms of values of one or more attributes are specified using sliders. The tool works according to the filtering principle: all data that do not satisfy the constraints are removed from the graphical display(s) linked to the query device. An important feature is that the displays immediately react to any changes in positions of the sliders by updating their contents according to the modified constraints. The dynamic query tool is easy to use but restricted with respect to the variety of possible questions. Thus, it is impossible to build a query with constraints linked by logical "OR" or involving comparison of values of two attributes, such as ‘‘When and where did the percentage of children exceed that of elderly people?’’

It has become customary in geovisualization software to enable access to data about individual spatial objects or locations through a map or other type of graphical data display. To receive the information, a user just needs to position the mouse cursor over an object or location on a map or graph. The position of the cursor specifies the query constraints (the objects or the coordinates of the location) while the target usually includes the name of the object and the corresponding values of the attributes represented on the display. This form of querying will be further referred to as ‘‘direct lookup’’. A direct lookup tool is often combined with other query devices.

Software packages dealing with spatio-temporal data usually include specific user interface facilities for temporal queries. Typically such facilities work as filters and are used for selection of time moments or intervals to be represented on the screen. In most systems the tools for temporal querying are built according to the view of time as a linear sequence of moments. Some systems additionally support the cyclic view of time. For example, Harrower et al. [24] describe an interactive query device called ‘‘temporal brushing’’ available in the system ESV (Earth Systems Visualizer); see also Harrower et al. [25]. This device may be used for choosing specific times of the day (e.g. 6 p.m.) and studying what happens at these times over many days. A particular value of this tool is the possibility to filter out diurnal fluctuations in spatio-temporal phenomena (e.g. climate) and look for long-term trends. In a similar manner, the system for analysis of traffic incidents described by Fredrikson et al. [26] allows the user to select days of the week. A sophisticated temporal query tool called ‘‘time wheel’’ (Fig. 2) is suggested in the system TEMPEST [27]. It allows an analyst to select arbitrary combinations of months within a year, days of months, and times

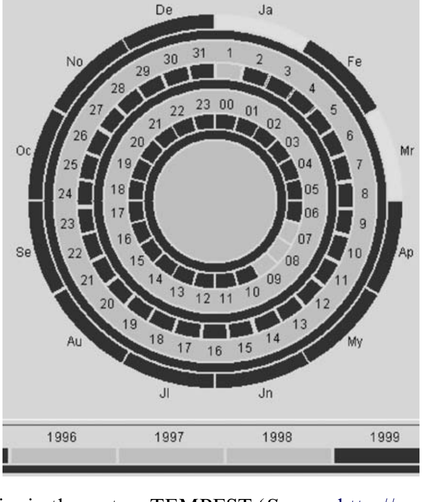

Fig. 2. Time wheel query device in the system TEMPEST (*Source:* http://www.geovista.psu.edu/products/demos/edsall/Tclets072799/cyclicaltime.htm).

of the day. Thus, the selection shown in Fig. 2 (brighter wheel segments) would allow one to investigate what happened on the first days of January and March during the hours from 7 a.m. until 10 a.m. in the years 1996, 1997, and 1998.

3.1.2. Map animation

The technique of map animation exploits the capability of the computer screen to rapidly update its contents: changes in data are represented by changes of a display. Map animation is present in almost all geovisualization packages that deal with spatio-temporal data. The system Vis-5D [28] animates perspective views of time-series data having three spatial dimensions (latitude, longitude and altitude).

Different software packages vary by the provided degree of user control over animation parameters. Below we enumerate animation parameters that may be potentially controlled:

- Speed.
- Direction: forth or back; arbitrary arrangement of animation frames.
- Extent, i.e. start and finish moments.
- Moments/intervals to include in animation:
  - Step, i.e. the interval between time moments successive animation frames refer to;
  - Moments or periods within a cycle;
  - Arbitrary selection.
- Smoothness (creation of intermediate frames by means of interpolation).

All systems have the functions of stopping and resuming animation. Additionally to animation, the user is often given an opportunity of manual stepping through time.

Similar to map animation is the technique of "fading" in the electronic Atlas of Switzerland [29–31]: a map or aerial photograph referring to one time moment gradually "fades" while a map or image for another moment becomes visible. This technique attracts analyst's attention to locations or areas where changes occurred.

3.1.3. Focusing, linking and arranging views

As we have already mentioned, Buja, Cook, and Swayne classify visualization techniques into three categories: focusing, linking and arranging views. Focusing techniques include the selection of subsets and variables (projections) for viewing and various manipulations of the layout of information on the screen: choosing an aspect ratio, zooming and panning, 3-D rotations, etc. Focusing results in conveying only partial information and, therefore, must be compensated by showing different aspects of data in multiple views. These multiple views need to be linked so that the information contained in individual views can be integrated into a coherent image of the data as a whole. The method of linking depends on whether the views are displayed in sequence over time or in parallel. In the first case, linking is provided by smooth animation. The most popular method for linking parallel views is identical marking of corresponding parts of multiple displays, e.g. with the same color or some other form of highlighting (see for example, [32]). Highlighting is often applied to objects interactively selected by the user in one of the displays. The purpose of arranging multiple views is to facilitate comparisons. A possible approach is to display each view in a separate window and allow the user to arbitrarily arrange the windows. Consideration of all possible solutions is beyond the scope of this paper.

The notions of focusing, linking and arranging views are very general and not related to any types of data or tasks. It is therefore not surprising to find these general techniques in nearly all visualization tools. Due to the highly generic character, we do not include these techniques in our review.

3.1.4. Map iteration

Basically, all methods traditionally used for representation of spatio-temporal data in conventional maps remain applicable to map displays on computer screens. Among them is the technique of map iteration, or "small multiples", according to Tufte [33], i.e. juxtaposition of several maps where each map shows the state of a phenomenon at a different time moment. Like map animation, this is also a universal technique in the sense of applicability to any type of spatio-temporal data. Obviously, the number of perceptible images that can be simultaneously shown on a computer screen is limited, and, hence, long time series have to be investigated at a rather coarse temporal resolution. Map iteration is available in the systems SpaTemp [22], Atlas of Switzerland, and MapTime [34].

Current software packages often combine querying, map animation and/or map iteration with more specific techniques applicable only to certain data types. Many of such specific techniques are inherited from the traditional cartography. In the literature, we have found various specific techniques suggested for representation and analysis of changes in existence, locations and thematic properties expressed through numeric attributes.

3.2. Existential changes

The system SpaTemp combines computer-oriented techniques for visualizing events with traditional cartographic representation methods. In particular, the system can show the time of appearing of an event or the period of its existence by labels. The "age" of events may be represented by variation of colors.

Fredrikson et al. [26] describe, by example of traffic incidents, how data about events can be explored using various ways of data aggregation: spatial, temporal and categorical (i.e. according to types of the events). The software displays summary characteristics of the aggregates, such as the total number of events or their average duration, and allows the user to "drill down" into each aggregate in order to see data about the individual events.

The summary data about spatially aggregated events (e.g. by road fragments) are shown on an interactive map by symbols the size of which is proportional to the number of events. Two different types of temporal aggregation are supported: by days of week and by calendar dates. In the first case, aggregates unite all traffic incidents that occurred on the same day of the week irrespective of calendar dates. The aggregates are represented by bars on a bar chart with the height of a bar proportional to the number of the events. In the second case, events that occurred on the same date are grouped together and shown on a calendar display using square symbols with sizes proportional to the numbers of incidents. It is possible to combine in such a display aggregated data for two different years or data for 1 year with averaged data for several years. This is done by means of overlaying symbols of two different colors. With any kind of aggregation, clicking on a symbol representing an aggregate (on a map, bar chart or calendar display) results in corresponding incidents being shown in a table view and in an additional map display. Data exploration by means of aggregation may be combined with querying using a dynamic query tool.

In our software system CommonGIS (an extended version of the system Descartes described in Andrienko and Andrienko [35]) data about events may be explored using the "space–time cube" representation [36, pp. 252, 254]. Here time is treated as the third (vertical) spatial dimension while two planar dimensions represent the geographical space. Events are represented as circles placed vertically according to the time of their occurrence (Fig. 3), the earliest events being at the bottom of the cube and the latest at the top. Variation of circle sizes or colors can additionally represent thematic characteristics of the events, for example, magnitudes of earthquakes.

Data exploration using the space–time cube is supported by a number of interactive operations. Thus, the user can change her/his viewing perspective into the

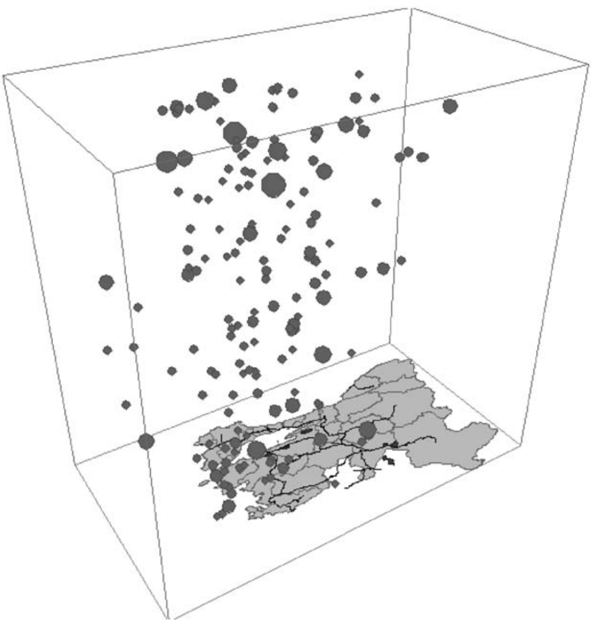

Fig. 3. Data about events are represented in a space–time cube. The vertical positions of the circles correspond to the times when the events occurred. Circle sizes or colors may reflect thematic characteristics of the events.

cube in order to check whether a bunch of circles really corresponds to a spatio-temporal cluster of events or this is merely a projection effect. It is possible to select a time subinterval and see only events that occurred during this time. The subinterval can be shifted along the time axis that results in the scene being dynamically redrawn.

An important feature of the space–time cube presentation is its dynamic linking with a map as well as graphical displays of other types. This means that corresponding objects are identically marked in all displays when the user selects them with the mouse in one of the displays. This technique is illustrated in Fig. 4: the user has selected a spatial cluster of events in the map and can see in the space–time cube how the events are distributed in time. In both the map and the cube these events are marked by circles with thick black boundaries.

3.3. Location changes

Modern software quite often applies conventional cartographic methods for representing location changes: lines connecting object positions at successive time moments, arrows indicating the direction of movement, and time labels showing when particular locations were visited. These representation techniques may be found, for example, in the system SpaTemp. The Atlas of Switzerland applies

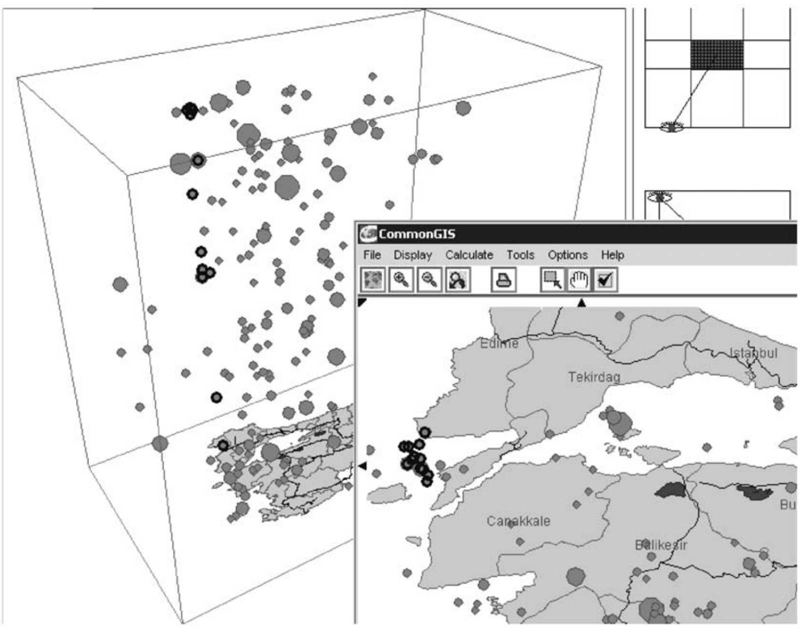

Fig. 4. The space–time cube is dynamically linked to the map display by simultaneous highlighting of corresponding elements.

the technique of "tracing": point symbols mark positions of a moving object from the beginning of the movement up to the currently represented time moment.

Static representation of routes in a single map has both strengths and weaknesses. Although it is convenient for analysis to have a view of the whole trajectory made by an object, this possibility is restricted to relatively simple trajectories and to a small number of moving objects for keeping the representation legible. A static representation is poorly suitable for analysis of the speed of movement. When routes of several objects cross, it may be hard to determine whether the objects really met at the crossing point or just visited it at different time moments.

Map animation may help to overcome the drawbacks of the static representation. There are three different variants of animated representation of object movement:

1. Snapshot in time: at each display moment the map shows only the positions of the objects at the corresponding real-world moment. Such animation variant is possible, for instance, in the system SpaTemp.
2. Movement history: the map shows the routes of the objects from the starting moment of the movement up to the currently represented moment. Hence, at the end of animation the whole routes are visible. In this way, for example, the "tracing" technique works in the Atlas of Switzerland. In SpaTemp the routes may be represented in the course of animation using lines or arrows.
3. "Time window": the map shows the fragments of the routes made during the time interval of a specified length (Fig. 5). This technique is described in more detail in (Andrienko et al. [37]).

MacEachren [36, p. 254] and Peuquet and Kraak [38] suggest that trajectories of object movement can be represented using the technique of space–time cube (Fig. 6). According to this technique, points in three-dimensional space, where the vertical dimension corresponds to time, represent the positions of an object at different time moments. Lines connect the points corresponding to consecutive moments. A demonstrator can be seen at http://www.itc.nl/personal/kraak/1812/minard-itc.htm.

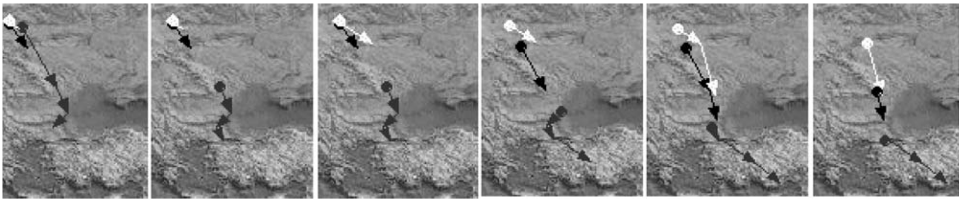

Fig. 5. The time window technique in animation of object movement. The screenshots represent the appearance of a fragment of a map at six consecutive animation moments. The length of the time window is 5 days, that is, each screenshot shows route fragments passed by the moving objects during 5 days. In the second and subsequent screenshots, the time window is shifted by 1 day forward relative to the preceding image. Note that movements of a particular object did not necessarily occur every day.

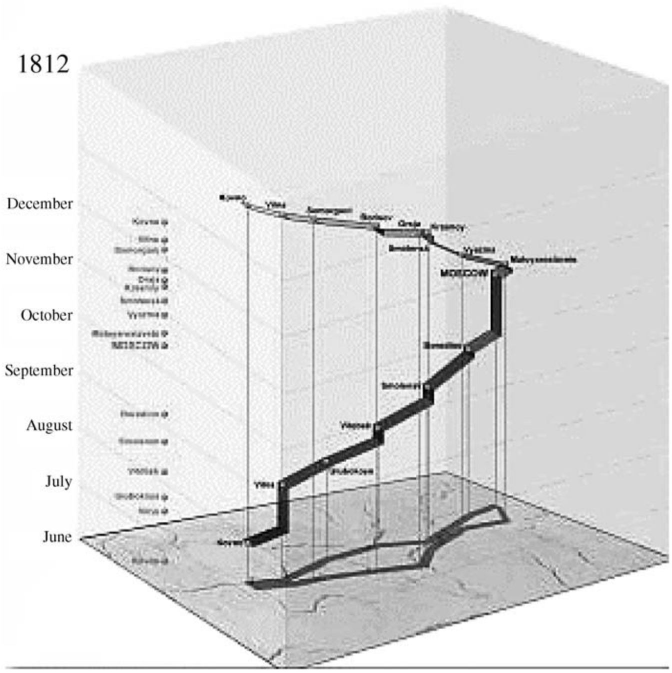

Fig. 6. Representation of object movement in a space–time cube (*Source*: *ITC-Minard* [39]).

3.4. Attribute changes

We did not find in the literature or in the Web any specific tools for studying qualitative changes while a variety of techniques are suggested for numeric data.

One of the techniques, the so-called "change map", is inherited from the conventional cartography. The idea is to show for each location or area the absolute or relative amount of change between two time moments. In the Atlas of Switzerland changes are represented by means of painting areas on a choropleth map in shades of two different colors: one color indicates increase of attribute values and the other decrease. The degree of darkness shows the magnitude of change. In MapTime, which is designed for exploring time-series thematic data associated with point locations, increases and decreases are represented by circle symbols of two different colors while circle sizes are proportional to the magnitudes of changes. In MapTime, one can produce and simultaneously view several change maps. In Atlas of Switzerland it is possible to combine the "change map" technique with animation. On each step of the animation the map represents the differences between two successive time moments while in the static mode it is possible to build a change map for arbitrary two moments. In Andrienko et al. [40] we describe a visualization tool of our own that, besides animating changes between successive moments, can also represent in the animation mode differences in comparison to a fixed user-selected moment.

Additionally to displaying data on maps, some software packages, for example, TEMPEST [27] and STEM [41], can show temporal variation of numeric attribute values at selected locations on a time-series graph. The *X*-axis of such a graph typically represents the time, and the *Y*-axis, the value range of an attribute. For a spatial object or location a line (‘‘value path’’) is built by connecting the positions corresponding to attribute values attained at consecutive time moments. Our visualization tool also includes a time-series graph representing simultaneously data about all spatial objects present in the map. Due to its interactivity and dynamic link to the map, the graph is a useful analysis tool even despite of cluttering and overlapping of the lines. Thus, the line or bundle of lines pointed on with the mouse is highlighted in the graph and, 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 highlighting of the corresponding line in the graph (see Fig. 7). Hochheiser and Shneiderman [42] suggest sophisticated interactive tools for data exploration with a time-series graph that, being combined with a map display, would be also very useful for exploring spatio-temporal data.

In the system STEM, overall trends in variation of numeric attribute values may be explored by means of spatio-temporal data aggregation. STEM aggregates data over all locations by user-specified time periods. For each period, the system may compute the mean value as well as other statistics: minimum, maximum, standard deviation and frequency of measurements. The data aggregated in this way are shown on a specific graphical display called ‘‘time bar’’. The bar is divided into segments corresponding to the aggregation periods. Each segment is colored according to the aggregated value for the respective time period.

3.5. Summary

By now we have considered various computer-enabled techniques for representation and exploration of spatio-temporal data from the perspective of their applicability to different types of data. Our observations can be summarized by grouping the techniques into four categories:

1. ‘‘Universal’’ techniques, i.e. applicable to all data types: querying (lookup and filtering), map animation and map iteration.
2. Techniques suitable for data about existential changes: time labels, representation of the age by color, aggregation of data about events and space–time cube.
3. Techniques applicable to data about moving objects: trajectory lines, arrows, ‘‘tracing’’, time labels, space–time cube and different animation modes, i.e. snapshot in time, movement history and time window.
4. Techniques for studying thematic (numeric) changes: change map, time-series graph and aggregation of attribute values.

Let us now consider these techniques from the perspective of their suitability for different types of exploratory tasks.

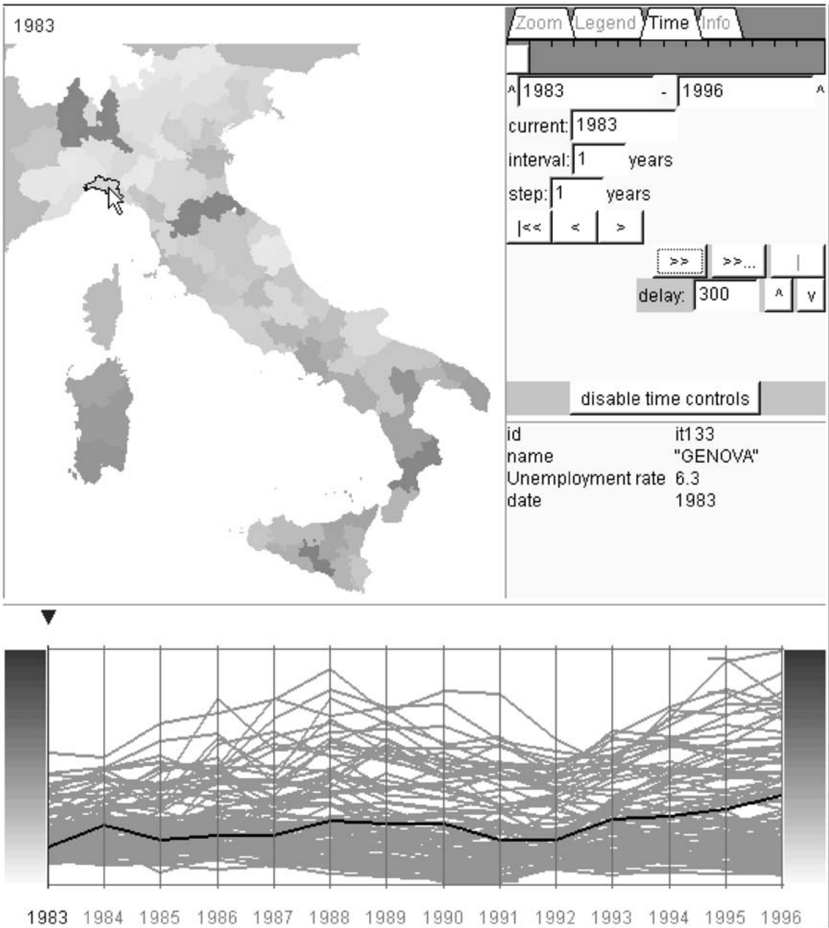

Fig. 7. An interactive time-series graph dynamically linked to a map. Highlighted in the graph is the line corresponding to the municipality of Genoa, which is pointed on the map by the mouse (*Source: http://borneo.gmd.de/and/time/italy.html*).

4. Exploratory techniques and data analysis tasks

4.1. Elementary tasks (with respect to time)

Elementary (with respect to time) tasks refer to individual time moments. According to our task classification scheme, these tasks can be further differentiated on the basis of the search target (time or locations/spatial objects), cognitive operation involved (identification or comparison) and search level with respect to space and objects.

4.1.1. When → what + where

In this task group, identification tasks have the goal to determine characteristics of spatial objects or locations at a given moment or moments. On the elementary (with respect to space and objects) level, an analyst is interested in characteristics of individual objects or locations. On the general level, the spatial distribution of objects or/and characteristics is in the focus of the study.

For this kind of identification tasks, a software system must be able to visualize data referring to a particular user-selected time moment. A data subset referring to a single time moment does not involve temporal variation and, hence, can be represented and operated as ordinary time-irrelevant spatial data. We are not going to consider in detail techniques and tools suitable for such data. Discussion of different cartographic representation methods from the perspective of the supported search level may be found, for example, in Bertin [19]. There exists an extensive literature describing various interactive techniques for exploratory analysis of time-irrelevant spatial data; see, for example, MacDougall [43], Dykes [44], Andrienko and Andrienko [35]. Besides identification tasks, some of these techniques can support comparison of objects or/and locations.

More pertinent to the focus of our paper are tasks involving comparison of two or more time moments. Such comparison tasks may refer to individual objects or locations (how did characteristics of this object change from moment t_1 to moment t_2?) or to a set of objects or a territory as a whole (how did the overall situation change from moment t_1 to moment t_2?). These are, in our terms, the elementary and general search levels with respect to space and objects.

In comparison of two time moments, an analyst pursues two subgoals:

- *Detect changes*: Did this object change? Did the pattern of spatial distribution change? Where did changes occur throughout the territory?
- *Measure changes*, that is evaluate their character, amount, direction, etc.: How much did this object change? How did the pattern of spatial distribution change? How do characteristics of change vary over the territory?

Change detection: From the universal exploratory techniques, the technique of map iteration (juxtaposition of maps representing situations at different moments) appears to be the most suitable for change detection. An evident advantage over, for example, map animation is the possibility to consider situations at two time moments simultaneously, being able to arbitrary shift the focus of attention from one map to the other. Detecting changes in the overall pattern of spatial distribution of objects or characteristics requires the maps to be perceived in their entirety, as integral images. Some cartographic representation methods are more favorable for such kind of perception than others; see Bertin [19] for discussion of associative capabilities of different visual variables.

In order to find places where changes occur, one needs to visually scan each map and compare fragments of the maps. Probably, this operation could be more effectively supported by overlaying one of the maps upon the other, the upper map being semitransparent. To our knowledge, none of the existing software packages enable this kind of overlaying whereas some of them offer a similar technique for representations of two or more spatial and spatio-temporal phenomena. Close to overlaying is the fading technique in the Atlas of Switzerland: one map gradually dims and eventually disappears while another map emerges from beneath of it.

Change measurement: While comparison of juxtaposed maps is quite appropriate for evaluating such characteristics of change as character or direction, it may be insufficient for estimating the amount or degree of change, i.e. for answering questions of the kind: How far did the object move? How much did the unemployment rate increase in this area?

For measuring changes of spatial characteristics of objects (i.e. location, shape, size or orientation), a suitable technique could be overlaying. Location changes can be easily measured when trajectories of objects are represented on a map by lines, as in SpaTemp, or "traces", as in Atlas of Switzerland. When there are many moving objects or/and the trajectories are complex, it is appropriate to apply filtering so that the map shows only the movements that occurred during a selected time interval.

Change maps are good for estimating changes in thematic properties expressed by numeric attributes. For accurate evaluation of the amounts of change, a change map may be combined with the direct lookup technique: the user points on an object/location on the map with the mouse cursor, and the corresponding amounts are displayed on the screen. Change maps supporting direct lookup are available, for example, in the Atlas of Switzerland.

Besides estimation of changes occurring to individual objects or locations, change maps allow an analyst to see the general pattern of change. For example, the change map in Fig. 8 shows differences in unemployment rates between years 1983 and 1990 by municipalities of Italy. There is a salient spatial pattern of changes: decrease of the unemployment rates on the north and increase on the south.

The task of revealing the general pattern of change is different from the task of evaluating the change of the general pattern of object or value distribution. For example, in exploring the data about the unemployment rates over Italy an analyst may be interested how the pattern of spatial distribution of the unemployment rates over the country changed from 1983 to 1990. For this kind of task juxtaposition of maps for 1983 and 1990, as in Fig. 9, is more appropriate than the change map. Thus, one may see in Fig. 9 that the overall spatial trend is common for the years 1983 and 1990: the unemployment rates increase in the direction from the north to the south. At the same time the distinction between the north and the south becomes in 1990 more contrasting than in 1983. This is indicated by considerable differences in the degrees of darkness used in the upper and in the lower parts of the map representing data for the year 1990 (on the right of Fig. 9). Spatial aggregation, e.g. grouping of the municipalities into north, center and south, and calculation of various statistics for the aggregates would allow an analyst to estimate numerically the degree of change of the spatial pattern. However, we are unaware of any software package enabling such operations. Existing data aggregation tools provide only statistics regarding a set of objects or a territory as a whole. For example, in the system STEM it is possible to compare mean attribute values over the whole territory at two or more time moments. The system for analysis of traffic incidents provides statistics either for the whole territory and

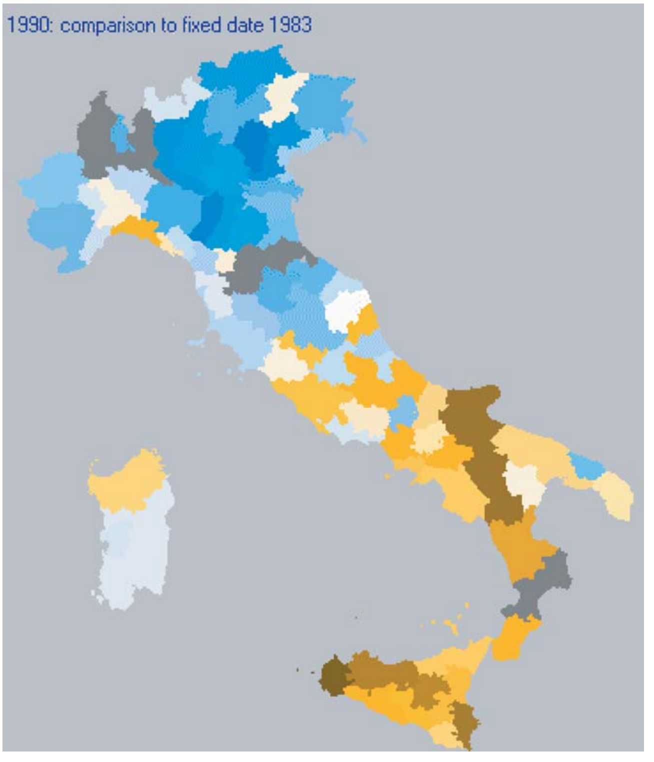

Fig. 8. The change map compares unemployment rates by municipalities of Italy in years 1983 and 1990. One may see a clear spatial pattern of change: decrease of the unemployment rates on the north (indicated by shades of blue) and increase on the south of the country where shades of brown prevail. The dark-gray areas correspond to missing data (*Source:* *http://borneo.gmd.de/and/time/italy.html*).

particular time moments or intervals or for particular locations but for the whole time period.

The techniques applicable to "*when*→*what*+*where*" tasks (elementary search level with regard to time) are summarized in the following Table 1.

4.1.2. *What + where → when*

In this sort of tasks, the goal is to determine the time moment(s) when specific characteristics of objects or locations occur.

Identification tasks on the elementary (with respect to space and objects) level may be supported by sufficiently sophisticated querying facilities. The characteristics of objects or locations (known information) need to be set as query constraints, and time (unknown information) as the query target. The same technique can be also used for comparison tasks in which an analyst needs to compare the time moments when different characteristics occurred in the same place or the same characteristics occurred in different places. Unfortunately, from the descriptions of the existing software packages it is unclear which of them (if any) support this sort of queries.

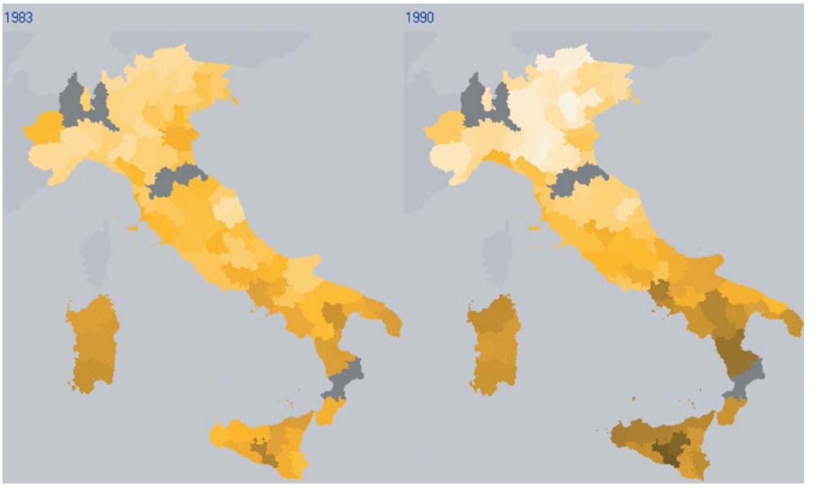

Fig. 9. Juxtaposition of maps showing value distributions at two time moment supports evaluation of the change of the distribution pattern. One may see that the contrast between the northern and the southern parts of Italy increased in 1990 as compared to 1983.

One can also search for time moments when some conditions were fulfilled (in terms of characteristics of objects or locations) by scanning a sequence of juxtaposed maps showing situations at different moments. Another suitable technique is "stepping" through time, a variant of animation when a display switches to representing the next time moment after a certain user's action rather than automatically. These two techniques are suitable both for elementary and general tasks, with respect to space and objects.

Besides these general approaches, specific opportunities exist for particular data types. Thus, for existential changes or object movement, there is a principal possibility to represent data for all time moments in the same map. The moment when some event took place or a given object visited a certain place can be easily identified from time labels or by means of direct lookup. For example, the date of an earthquake may be displayed when the mouse cursor is positioned over the circle representing this earthquake. Similarly, positions along a trajectory of an object may also be mouse-sensitive and respond with the dates when the corresponding places were visited. Time stamps and direct lookup facilities are also helpful in comparison tasks. However, they can only support the elementary search level.

In the case of changing values of numeric attributes, simple identification and comparison tasks of the type "*what + where → when*" may be fulfilled using an interactive time-series graph (see Section 3.4 and Fig. 7), which can be specially transformed to facilitate comparisons. For example, in order to answer the question "When did the unemployment rate in Rome reach the level 10% or more?", one can switch the time graph into the mode of comparison to a particular value and set 10 as the reference value to compare with. A straight horizontal line corresponding to this value appears on the time-series graph. Now the user needs to make the line of Rome

Table 1
Summary of the techniques supporting *when*→*what*+*where* tasks on the elementary level with respect to time

Cognitive operation	Search level (regarding space and objects) Elementary	 General
Identify	Cartographic representation methods supporting the elementary search level, e.g. chart maps Direct lookup Dynamic link between maps and other displays ("brushing")	*Summary for a territory or object set in whole*: data aggregation *Spatial distribution*: cartographic representation methods supporting the general search level, e.g. choropleth maps or dot maps
Compare Objects (locations)	*see above*	Juxtaposition of maps representing different phenomena or different territories at the same time moment Overlaying different phenomena in the same map
Time moments	Map iteration Map overlaying	Map iteration *Numeric attributes*: change map
Detect change	Fading *Numeric attributes*: change map	
Measure change	Map overlaying *Moving objects*: static trajectory representation (lines, arrows, or traces). May be combined with filtering. *Numeric attributes*: change map combined with direct lookup	*Change of spatial pattern*: map iteration; data aggregation by parts of territory (for events or numeric attributes) *General spatial pattern of change*: change map (for numeric attributes) *Summary change for the whole territory*: data aggregation

Gray background corresponds to time-irrelevant techniques not being considered in detail in this paper.

highlighted in the graph by pointing or clicking on Rome in the map display (see Fig. 10). Now, it may be easily seen that the unemployment rate in Rome was over 10% in the years from 1994 to 1996. It is more difficult to see from the graph whether the 10% level was reached in the years 1986, 1988–1990, and 1993. However, it is possible to use the direct lookup tool to see the exact values for these years.

Using the time-series graph, one can easily determine at what time moments the attribute value for a given object was the highest or the lowest as well as when the highest or the lowest value among all objects was attained. Thus, from Fig. 10 it may be seen that the highest unemployment rate in Rome was in 1996, and in the same year the maximum unemployment rate over Italy was achieved. The unemployment rate in Rome was at the lowest level in 1983 whereas the overall minimum over Italy was attained in 1990 and 1991.

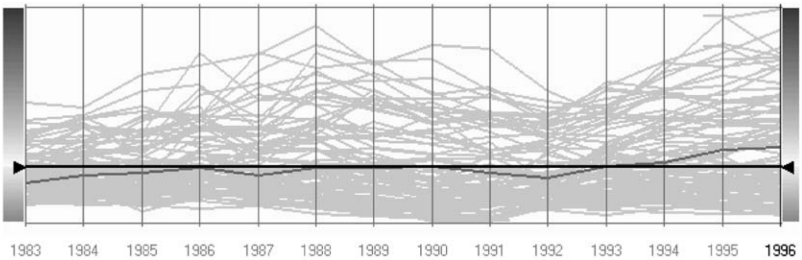

Fig. 10. The appearance of the interactive time-series graph in the mode of comparison to a particular attribute value. The value is represented on the graph by a straight horizontal line. Through the map display the user may select some geographical object and compare its value path (it is highlighted in the graph) with the line for the specified reference value.

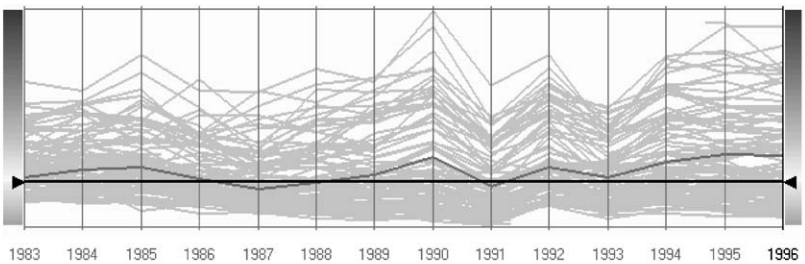

Fig. 11. The time-series graph in the mode of comparison with a particular object. The value path of the reference object is represented by a straight horizontal line. For all other objects, the graph represents the differences between the corresponding attribute values and the values for the reference object at the same time moments.

The mode of comparison with a particular object supports answering questions like “When was the unemployment rate in Rome lower than that in Pisa?” In this mode, the time-series graph is transformed so that the value path of a specified reference object (e.g. Pisa) becomes straight. For all other objects, the graph represents the differences between the corresponding attribute values and the values for the reference object at the same time moments (Fig. 11). Now the user needs again to select Rome in the map and compare the line for Rome with the straight line for Pisa. From Fig. 11 it is clearly seen that the unemployment rate in Rome was lower than in Pisa in the years 1987 and 1991.

A time-series graph is typically less suitable for answering questions referring to multiple attributes since it represents values of only one attribute. However, in the system STEM it is possible to represent on a time graph up to five different attributes and up to five different objects or locations. Assuming that the lines for different attributes and different objects are well discernible, such a graph can support rather sophisticated exploratory tasks.

A time-series graph is suitable for tasks referring to characteristics of individual objects or locations (i.e. elementary tasks) but not for general tasks addressing a set of objects or a territory as a whole. Data aggregation tools can support certain kinds

Table 2
Summary of the techniques supporting "*what + where → tasks*" on the elementary level with respect to time

Cognitive operation	Search level (regarding space and objects)	
	Elementary	General
Identify	Querying	Map iteration
	Map iteration	Map animation (time stepping)
	Map animation (time stepping)	*Events or numeric attributes*: data aggregation; provides only a summary for a set in whole
	Events: static map display + time stamps or direct lookup	
	Moving objects: static trajectory representation + time stamps or direct lookup	
	Numeric attributes: interactive time-series graph	
Compare	Same as above, with the exception of the map animation	Same as above, with the exception of the map animation

of general tasks, specifically, questions about summary characteristics of a set or a territory in whole, for example, when did the mean unemployment rate over Italy exceed 10% (reach the highest level)? However, aggregation tools are inadequate for tasks concerning the spatial distribution of characteristics. The same applies to aggregation tools dealing with data about events.

A synopsis of the techniques appropriate for "*what + where → when*" tasks (elementary level regarding time) is given in Table 2 above.

4.2. *General tasks (with respect to time)*

Tasks of this kind refer to time intervals. An analyst is interested in dynamics of characteristics of an object (location) or set of objects (locations) over these intervals. Let us use the term "behavior" to denote the entire course of changes an entity or set undergoes during a time interval. Tasks of general search level with respect to time address behaviors in whole rather than states at different individual moments or solitary changes from one moment to another.

4.2.1. *When → what + where*

In this group of tasks, an analyst identifies characteristics of a behavior or compares behaviors over a given time interval or intervals.

Elementary tasks, with respect to space or objects, address behaviors of individual objects or locations. An analyst can identify the behavior of an object or location by observing it during map animation or on a series of maps referring to consecutive time moments (map iteration). Filtering facilitates focusing on a particular object among other objects.

In comparing behaviors, different cases are possible:

- compare behaviors over the same time interval:
  - compare homogeneous behaviors, for example, compare the movements of the white storks *X* and *Y*; compare the dynamics of average house prices in the cities A and B;
  - compare (relate) heterogeneous behaviors, for example, relate the movement of the stork *X* to the air temperature and precipitation at the visited sites; compare the dynamics of average house price and unemployment rate in the city A;
- compare behaviors on distinct time intervals or subsets (usually this applies to homogeneous behaviors): compare the migration behaviors of the stork *X* in the years 2000 and 2001; compare the dynamics of house prices in the city A in spring and in autumn.

Let us first consider the situation with homogeneous behaviors on the same interval. This involves consideration of two or more distinct objects or locations. Hence, in the course of viewing an animation or scanning a map sequence, an analyst needs to focus simultaneously on these multiple objects or locations. At the same time, she/he needs to perceive the behavior of each object or location as an integral process. Switching the attention from one object (location) to another greatly impedes such perception. Therefore, it seems more appropriate first to identify each behavior separately (for example, by viewing the animation several times with focusing on different objects or locations) and then compare their general characteristics. This, of course, requires the behaviors to be memorized.

Potentially applicable is synchronous display of two juxtaposed animations, each showing the behavior of one object or location. It is, however, unclear whether an analyst can effectively watch two simultaneous animations. This needs to be empirically tested.

For comparing heterogeneous behaviors at the same or spatially close places, it is convenient when the data about the behaviors are overlaid on the same display. Such a display can be animated or iterated. For example, a map on each step of animation can simultaneously represent the position of a white stork by a circle symbol, variation of air temperature over the territory by coloring, and precipitation by heights of bars positioned at sample sites.

Homogeneous behaviors occurring over distinct time intervals may be compared by means of viewing two or more animations sequentially or simultaneously. Since each animation plays in this case its own sequence of time moments, it may be interesting to experiment with selecting different starting moments and different animation steps. In this way an analyst can detect, for example, that one behavior is similar to the other but develops two times faster.

Besides these common techniques, there are specific techniques for different data types that may also support identifying and comparing individual behaviors.

For events (i.e. objects undergoing existential changes) that do not revive a behavior is fully identified by the starting moment and duration or ending moment of an event. This information may be conveyed by a static map display with time

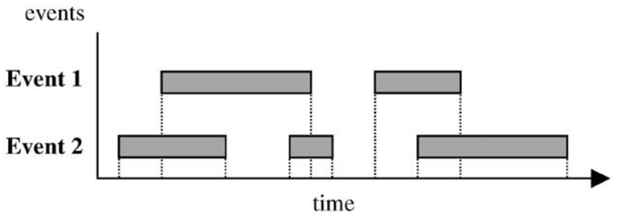

Fig. 12. A chronological graph representing existence periods of two reviving events.

stamps or with direct lookup facilities. Event duration can be represented by symbol sizes. Such a display is also sufficient for comparison of behaviors of two or more events. However, these techniques do not help if events can resume their existence. In such a case investigation and comparison of individual behaviors could be supported by a chronological graph, which represents the periods of event existence by bars as is shown in Fig. 12 (this representation is often used in historical literature). The graph must be linked to a map showing the event locations.

Data about events can be also viewed from a different perspective. One may wish to investigate the temporal pattern of event occurrences at a particular place. Such a task can be fulfilled using the interactive space–time cube display described in Section 3.2. Especially helpful may be the dynamic link between the cube and the map illustrated in Fig. 4.

For moving objects, the notion of behavior includes the trajectory of movement and speed characteristics. For identifying and comparing trajectories, it is convenient to have the paths represented on a map by lines or arrows. Paths made during distinct time intervals may be conveniently compared using juxtaposed maps each representing one of the intervals. However, static representation of trajectories is not appropriate for exploration of the speed of movement. For this purpose, an animated presentation is more suitable. In Section 3.3 we mentioned three variants of animated representation of object movement: "snapshot in time", "movement history", and "time window". Let us now compare these variants from the perspective of their support in exploring speed characteristics of object movement.

The variant "snapshot in time" is suitable for exploring movement of a single object. With several objects, however, it may be difficult to keep all the objects in the focus of attention. The variant "movement history", in which the current position of every object is graphically linked to its previous position, may prevent the analyst from loosing track. However, after several steps of animation the "tails" representing past movements may become very long or/and very complex (e.g. self-crossing) and distract the analyst from perceiving current movements. The "time window" animation mode cuts the "tails" and shows only a few movements preceding the currently represented moment. Thereby, the advantages of the "movement history" mode are preserved while the shortcomings can be reduced. In our experiments, we found the "time window" mode the most convenient for exploration and comparison of behaviors in terms of the speed of movement [37]. In this mode (Fig. 5) information about object motion is conveyed by arrow chains that move over the map. The chains represent path fragments made during time periods of a constant extent. The lengths of the chains thus show the distances passed during this extent of time and, hence, allow the analyst to estimate the speed of movement. Shrinkage of a chain in the course of animation signalizes that the movement of the corresponding object slows down, and expansion means that the movement becomes faster. When an object stops its motion and stays for some time in the same place, the corresponding chain reduces to one dot.

The technique of "space–time cube" [36,38] in application to data about movement allows an analyst to see the trajectory (it may be projected onto the bottom face of the cube) and at the same time explore the speed of movement using the three-dimensional representation (see Fig. 6). In this representation, gently sloping path segments indicate fast movement, i.e. long distance in space traveled in short time, while steep segments correspond to slow motion. Vertical lines occur when an object stays for some time period in the same place. The "space–time cube" technique appears to be more suitable for identifying the behavior of a singular moving object than for comparison of behaviors, since representation of several trajectories in the same cube can make the display illegible.

Behaviors in terms of temporal variation of numeric attribute values can be effectively analyzed and compared using a time-series graph linked to a map. Representation of a behavior by a value path facilitates its integral perception. A value path is good both for estimating the general trend of changes and for analyzing the speed. Here steep line segments correspond to rapid changes while flat segments indicate periods of little or no change. The direction of change (increase or decrease) is reflected in line inclination (up or down). A time-series graph can be applied both for comparing variations of values of the same attribute at different places (homogeneous behaviors) and for comparing value variations of different attributes at the same or different locations (a specific case of heterogeneous behaviors). For a more sophisticated analysis of individual behaviors, one may apply the statistical methods suited for time-series data (see for example [3]).

In various specific cases comparison of heterogeneous behaviors can be supported by combining graphical displays of different types, depending on the types of data. Thus, a combination of a map showing movement and a time-series graph showing variation of air temperature is used in the well-known representation of Napoleon's Russian campaign of 1812 created by Minard (cited, for example, in Vasiliev [1] and Peuquet and Kraak [38]). In order to refer locations on the map to the marks on the graph showing the temperatures at the time moments when these locations were visited, Minard connected them with lines. In computer displays, other linking techniques are typically used; we have briefly discussed them in Section 3.1.3.

General tasks regarding space or objects refer to changes occurring to a set of objects or a territory. One can investigate such changes on different levels of abstraction. Thus, an analyst may be interested in summary characteristics about an object set or a territory expressed through some statistical indices such as the total number of events or the mean (minimum, maximum) attribute value. For such a kind of tasks, the techniques involving data aggregation are appropriate. Behaviors of object sets or territories in terms of their summary characteristics can be explored using various non-cartographic displays such as a time-series graph, time bar, as in the system STEM, bar chart and calendar display, as in the system for analysis of traffic incidents, and so on.

More complex are tasks involving exploration of changing spatial patterns. Such tasks can only be done with the use of map displays. General techniques to support behavior identification are map animation and map iteration. In both cases the maps should be designed in such a way that integral perception of the entire territory is enabled (see [19]).

As for individual behaviors, various situations of comparing general behaviors are possible:

- compare heterogeneous general behaviors on the same territory during the same time interval, for example, compare the dynamics of rainfall and vegetation;
- compare homogeneous general behaviors on distinct territories during the same or different time intervals, for example, compare the processes of city growth in France and Germany;
- compare general behaviors on the same territory during different time intervals (this usually makes sense for homogeneous behaviors), for example, compare the spatio-temporal variation of air temperature over Germany during the first and the second weeks of June.

For comparing behaviors that occur within the same space–time frame, it is convenient to have them overlaid in a common map display. When two or more continuous phenomena are represented on a single map, special techniques are required for ensuring visibility of all of them. Thus, a phenomenon shown on top of other geographic information needs to be displayed in a semi-transparent mode. Another helpful technique is filtering. For example, Blok et al. [45] describe a combined animated representation of rainfall and vegetation in Kenya where filtering is applied: only values over 60 mm for rainfall and over 0.4 for the vegetation index are shown on the map by means of coloring. For each phenomenon all values satisfying the filter constraints are represented on the map using one and the same color (Fig. 13). An analyst should be able to interactively change filter constraints.

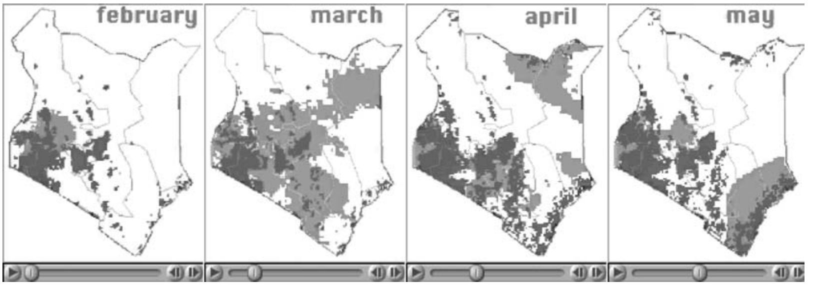

Fig. 13. Animated representation of two continuous phenomena (rainfall and vegetation) overlaid in the same map display. The blue color represents rainfall values over 60 mm, and the green color is used for vegetation index values over 0.4. The rainfall data are represented in a semi-transparent way to keep the information beneath visible. (*Source*: *ITC-Kenya* [46]).

Advanced facilities for comparing behaviors of several spatio-temporal phenomena shown on the same map display are provided in the system TEMPEST. The tool for controlling map animation in the system is an interactive scrollable time line. When several dynamic phenomena are represented on the map (as overlaid map layers), the system generates a separate time line for each phenomenon. There are three opportunities for manipulation of the time lines:

1) The time lines are manipulated independently. In particular, the user can examine the behavior of one of the phenomena while keeping the displayed time for the others fixed. This gives an opportunity to see whether the behavior is related to spatial distributional patterns of the other phenomena at a certain time moment.
2) The time lines can be bound to one another and move synchronously, with common displayed time for all the layers. The user can inspect whether behaviors of different phenomena are correlated.
3) When binding the time lines together, the user may specify an offset for each of them so that the layers change simultaneously, but with a specified lag between the individual times displayed. This function allows the analyst to investigate cause–effect relationships between phenomena when effects caused by events or changes appear after a delay.

Besides overlaid representation of multiple phenomena in a single map display, Blok et al. [45] introduce other methods for comparing heterogeneous behaviors occurring on the same territory during the same time period. One of them is juxtaposed display of two animations, each showing the behavior of one phenomenon. The animations may be run independently or synchronously, hence, the user may view them sequentially or simultaneously. In a synchronous display, it is possible to select for each phenomenon a different starting moment of animation. This can help in detecting lagged correlations. Another method suggested by Blok et al. is representation of two behaviors in the same display by alternating representations of the phenomena in the course of animation.

Behaviors occurring on different territories can be compared using two (or more) animated map displays viewed sequentially or in parallel. For revealing similarities it may be useful to experiment with different starting moments or/and steps of the animations. Juxtaposed or sequential animations are also suitable for comparing behaviors occurring during different time periods. If the behaviors take place on the same territory, it is possible to overlay or alternate them in the same display. In such a case, even homogeneous behaviors need to be represented differently so that an analyst could distinguish them. It should be noted, however, that we are not aware of any existing software that could support comparison of spatially or temporally disjoint behaviors.

From data-specific techniques, representation of events in a space–time cube as described in Section 3.2 may be supportive for tasks of the general search level with respect to both time and space/objects. Such a representation provides an opportunity to grasp the overall spatio-temporal pattern in one sight. In particular, it exposes spatio-temporal clusters of events that one may, probably, see less clearly from map animation or map iteration. In order to compare behaviors of two sets of events, one may represent them in two juxtaposed space–time cubes to be viewed in parallel.

In investigation of spatio-temporal variation of thematic characteristics expressed through numeric attribute values, representation of original data on animated map displays or map sequences can be aptly complemented by animated or juxtaposed change maps. Change maps are particularly useful for estimation of amounts or degrees of changes. Animated change maps may facilitate perception of the speed of changes and its variation over time.

Let us summarize the techniques that may be useful for fulfilling general (with respect to time) "*when* → *what* + *where*" tasks (Table 3).

4.2.2. *What + where → when*

This kind of general tasks involves search for time intervals during which a specific behavior took place. On the elementary level with regard to objects or/and space this is the behavior of an individual object or dynamics of characteristics at a particular place, for example, in what hours of the day does the number of incidents at this road junction increase? During what time interval did the stork X fly to the north? When did the unemployment rate in Rome go down? On the general level, an analyst considers the behavior of a set of objects or how distribution of characteristics over a territory develops in time, for example, on what days of the week does the number of traffic incidents in the city outskirts exceed that in the center? Were there periods of synchronous movement of all storks in the same direction? During what time periods did the unemployment rates mostly decrease throughout the whole Italy? In comparison "*what* + *where* → *when*" tasks an analyst compares time periods when two or more different behaviors took place, i.e. determines whether these periods are the same, adjacent, overlapping or temporally separated, which one is longer, etc.

Fulfilling this kind of tasks requires an analyst, first, to detect the behaviors of interest, second, to determine the time frame of these behaviors. The technique of map animation appears to be quite suitable for the first subtask. Once a particular behavior has been noticed, the analyst requires tools for moving arbitrarily back and forth through time for determining the starting and ending moments of the behavior.

The map iteration technique appears to suit both subtasks. An analyst can compare situations at consecutive time moments and see whether the changes correspond to the behavior she/he is looking for. Once the beginning or the end of the behavior is detected, the time reference is immediately seen from the time label of the corresponding map. For comparison "*what* + *where* → *when*" tasks, map iteration also seems better suitable than map animation. However, map iteration has certain limitations, which were mentioned in Section 3.1.4.

Let us consider data-specific techniques that may be appropriate for "*what* + *where* → *when*" tasks. The interactive space–time cube can support tasks addressing events. This representation is especially suitable for detecting particular kinds of behaviors such as event sequences occurring at the same place shortly one after another. The corresponding symbols will be vertically aligned in the cube, as may be seen in Fig. 14. For determining the time frame of a detected behavior it is

Table 3
Summary of the techniques supporting general (with respect to time) tasks of the type "*when*→ *what*+*where*"

Cognitive operation	Search level (regarding space and objects)	
	Elementary	General
Identify	Map animation	Data aggregation; provides only a summary for a set in whole
	Map iteration	Map animation
	Events: static map display with time stamps or direct lookup; space–time cube	Map iteration
	Moving objects: static trajectory representation with time stamps or direct lookup; animated trajectory representation; trajectory in a space–time cube	*Events*: space-time cube
	Numeric attributes: time-series graph, statistical analysis methods	*Numeric attributes*: animation of change maps; iteration of change maps
Compare	Map animation: Overlay of two behaviors within the same display Independent animation of each behavior; Synchronous animation of two behaviors in distinct displays	Data aggregation; provides only a summary for a set in whole
	Map iteration	Map animation: Overlay of two behaviors within the same display, possibly, using transparency and filtering; Independent animation of each behavior; Synchronous animation of two behaviors in distinct displays; alternating animation of two behaviors within the same display
	Events: static map display with time stamps or direct lookup + symbol sizes representing durations; chronological graph (for durable and reviving events); space-time cube	
	Moving objects: static trajectory representation on the same map or juxtaposed maps; animated trajectory representation	
	Numeric attributes: time-series graph, statistical analysis methods	*Events*: juxtaposed space–time cubes
	Heterogeneous behaviors: linked displays	

convenient to use the movable plane that visually separates events having occurred before a specified time moment from later events (Fig. 14, bottom). The same technique supports comparison of time frames for two or more different behaviors. A similar analysis is possible with a space–time cube representing behaviors of moving objects. In such a cube it is easy to detect such behaviors as staying in the same place (manifested by vertical trajectory segments), slow movement (steep segments), and fast movement (gently sloping segments).

Particular individual behaviors in terms of changing values of numeric attributes are easy to detect and locate in time using an interactive time-series graph.

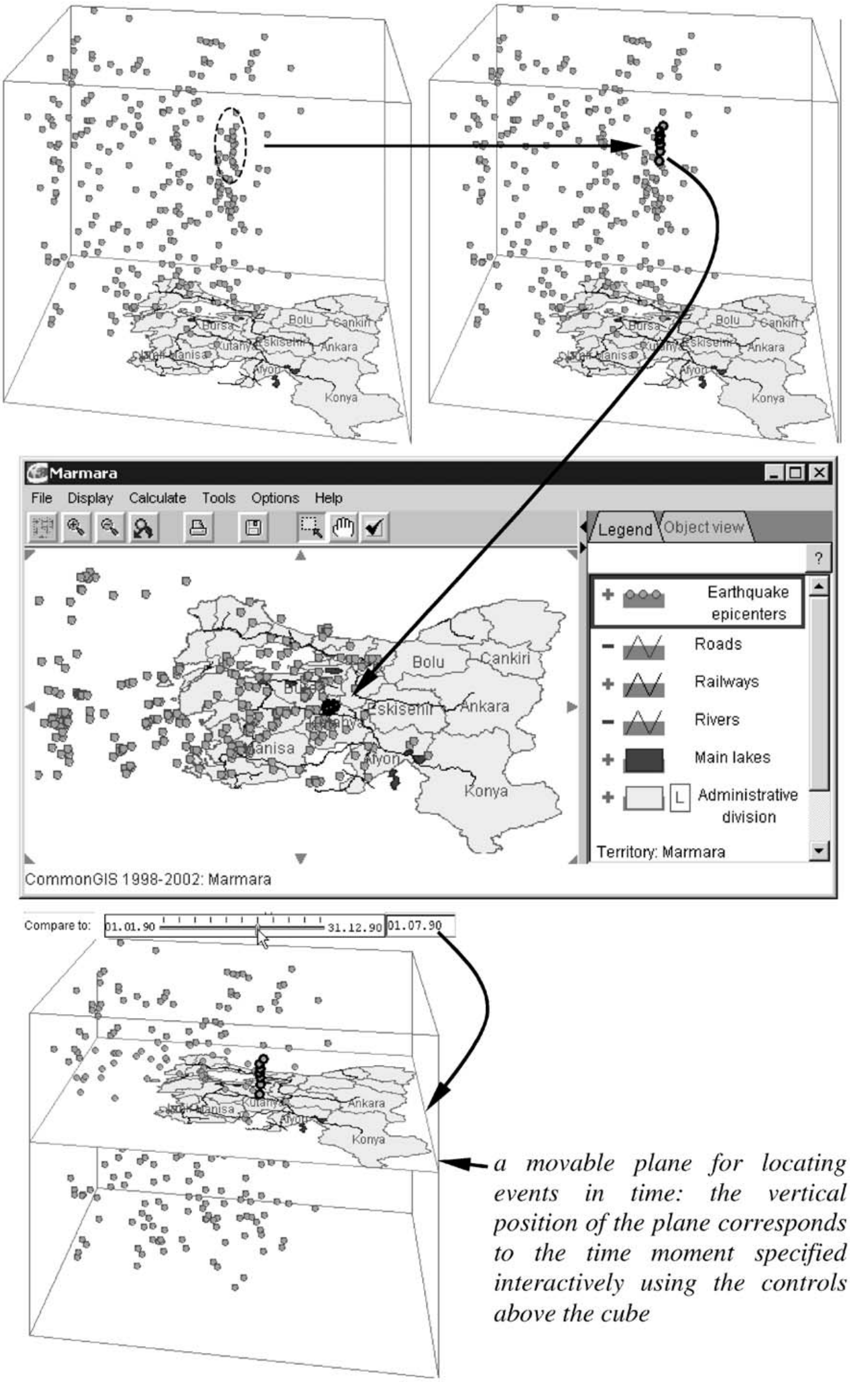

Fig. 14. A sequence of events occurring at the same place within a short-time period is manifested in a space–time cube by vertical alignment of symbols (upper left). The dynamic link between the cube and a map display helps the user to locate the event sequence in space (upper right and center), and the movable plane (bottom left)—in time.

Table 4
Summary of the techniques supporting general (with respect to time) tasks of the type "*what* + *where* → *when*"

Cognitive operation	Search level (regarding space and objects)	
	Elementary	General
Identify	Map iteration Map animation (time stepping)	Map iteration Map animation (time stepping)
	Events and moving objects: space–time cube	*Numeric attributes*: change maps + time stepping; iteration of change maps
	Numeric attributes: time-series graph	*Events and numeric attributes*: data aggregation; provides only a summary for a set in whole
Compare	Map iteration	Map iteration
	Events and moving objects: space–time cube	*Numeric attributes*: iteration of change maps
	Numeric attributes: time-series graph	*Events and numeric attributes*: data aggregation; provides only a summary for a set in whole

Comparison of time periods of different individual behaviors is also quite convenient to do with such a representation. Animated or iterated change maps may be more effective for determining when a specific general behavior begins and ends than animated or iterated maps representing original data. Thus, on a change map, a switch from increase of attribute values to decrease or vice versa is manifested by an abrupt change of color that is quite easy to detect. Dynamics of summary characteristics of a territory or object set as a whole is explored using data aggregation techniques.

The techniques estimated as appropriate for "*what* + *where* → *when*" tasks are summarized in Table 4.

5. Conclusion

The aim of our study was to create a catalogue of existing techniques supporting exploratory analysis of spatio-temporal data. As information sources, we used the available literature on data visualization and demonstrators found in the Web. We have also included in the review some tools designed by our team. All systems and demonstrators we have reviewed are listed in the appendix. In compiling the catalogue we disregarded the peculiarities of technique implementation in different packages. For example, we did not compare the specific map animation facilities of the systems TEMPEST and STEM but rather considered the map animation technique in general.

Our intention was to evaluate the existing techniques from the perspective of the types of data they can be applied to and types of exploratory tasks they can support. We considered the following types of spatio-temporal data, depending on the character of changes they reflect: (1) data about events, i.e. spatial objects undergoing existential changes; (2) data reflecting changes in spatial properties of objects, in particular, locations; (3) temporally varying values of thematic attributes. For our research we devised an operational typology of possible exploratory tasks, mostly on the basis of the notions of question types and reading levels introduced by Bertin [19]. According to Koussoulakou and Kraak [20], we applied the notion of reading levels individually to the spatial, temporal, and object components of spatio-temporal data ("where", "when", and "what") and considered the possible combinations. We also extended Bertin's classification scheme by introducing an explicit distinction between identification and comparison tasks. The resulting task typology, besides providing a basis for our evaluation and systemization of the techniques, may be useful for developers of geovisualization tools: it gives an opportunity to anticipate the questions prospective tool users might seek to answer. On this basis, the developers can design the tools so that they properly satisfy the users' needs.

The main result of our study is the established links between the exploratory techniques and the types of data and tasks they are appropriate for. The correspondences are summarized in Tables 1–4. They can provide guidelines for selection of techniques for data analysis depending on characteristics of data to analyze and tasks to be fulfilled. For end-users of geovisualization tools, it would be convenient if an expert system could advise them which techniques to utilize in what situations. The knowledge base of such a system could be built from the suggested catalog of techniques.

At the same time the catalogue may be useful for researchers in the area of visualization that can, on the one hand, see what task/data types are yet insufficiently supported by the existing tools and direct their creative activities towards filling the gaps, on the other hand, use the techniques described as basic elements for designing new, more sophisticated ones. The catalogue may also help developers of various domain-specific applications of geovisualization tools to appropriately select and combine the tools according to users' needs.

We recognize, however, that the appropriateness of the techniques for the tasks has been judged on the basis of the general principles of graphical representation of information, commonsense knowledge and our own experience in design and development of geovisualization tools and building of various applications for particular data and tasks. It is certainly necessary to check our results empirically, i.e. to test whether users can really utilize the techniques for fulfilling the tasks they are expected to support. We are open for collaboration with interested parties in such a kind of research.

Appendix. A

Software systems and demonstrators are shown in Table 5.

Table 5
Software systems and demonstrators reviewed in the paper

System acronym or designation in the paper	Source of information	Exploratory techniques provided[a]
Vis-5D	Hibbard et al. [28]	Animated perspective view of three-dimensional spatial data
TEMPEST	Edsall and Peuquet [27]	Temporal querying on the basis of linear and cyclic time models Overlaid animations of multiple phenomena (same or different starting moments) Time-series graph
SpaTemp	Stojanovic et al. [22]	Time labels Display of trajectories (arrows) Representation of event age by color Map iteration Overlaid animations of multiple phenomena (same starting moment)
ITC-Ameland [47]	Blok et al. [45] http://www.itc.nl/~carto/research/webcartoforum/ameland.html	Overlaid animations of multiple phenomena (same starting moment) Juxtaposed animations Alternating animations
ITC-Kenya [46]	Blok et al. [45] http://www.itc.nl/~carto/research/webcartoforum/kenya.html	Overlaid animations of multiple phenomena (same or different starting moments) Juxtaposed animations
Traffic incidents	Fredrikson et al. [26]	Temporal, spatial, and categorical data aggregation Linear and cyclic time models in data aggregation and querying Dynamic query
Atlas of Switzerland	Hurni et al. [29]	Display of trajectories (tracing, arrows)
	Oberholzer and Hurni [31]	Change maps; animated change maps
	Atlas of Switzerland [30]	Fading (smooth transition between two images)

Table 5 (*continued*)

System acronym or designation in the paper	Source of information	Exploratory techniques provided[a]
ESV	Harrower et al. [24]	Temporal querying on the basis of linear and cyclic time models
	Harrower et al. [25]	Overlaid animations of multiple phenomena (same starting moment)
STEM	Morris et al. [41]	Data aggregation, in particular, by time intervals Time-series graph
MapTime	Slocum et al. [34]	Map iteration Change maps; iteration of change maps
ITC-Minard [39]	Peuquet and Kraak [38] http://www.itc.nl/personal/kraak/1812/minard-itc.htm	Space–time cube (trajectory representation)
CommonGIS	www.CommonGIS.de	Space-time cube (event representation) Dynamic query
Other visualization tools developed by our team	Andrienko et al. [37]	Display of trajectories (arrows)
	Andrienko et al. [40] http://borneo.gmd.de/and/nd2002/dataview.html http://borneo.gmd.de/and/nd2002/routeapp.html http://borneo.gmd.de/and/time/	*Three map animation modes*: snapshot, movement history and time window *Change maps*; animated change maps Interactive time-series graph "Visual comparison" to previous time moment, fixed time moment, selected object or fixed attribute value

[a] Techniques common for all or almost all systems, such as map animation or querying, are mentioned in the table only in a case of peculiar implementation.

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