preprint : November 2004 - do not redistribute.

Exploring Geovisualization
J. Dykes, A.M. MacEachren, M.-J. Kraak (Editors)
© 2005 Elsevier Ltd. All rights reserved.

Chapter 10

Impact of Data and Task Characteristics on Design of Spatio-Temporal Data Visualization Tools

Natalia Andrienko, Gennady Andrienko & Peter Gatalsky, Fraunhofer AiS – Institute for Autonomous Intelligent Systems, Schloss Birlinghoven, Sankt-Augustin, D-53754, Germany

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

Abstract

It is widely recognized that data visualization may be a powerful methodology for exploratory analysis. In order to fulfill this claim, visualization software must be carefully designed taking into account two principal aspects: characteristics of the data to be visualized and the exploratory tasks to be supported. The tasks that may potentially arise in data exploration are, in their turn, dependent on the data. In the chapter, we present visualization software tools for three different types of spatio-temporal data developed using a task-driven approach to design. We demonstrate that different exploratory tasks may be anticipated in these three cases and that different techniques are required to properly support exploration of the data. Prior to the consideration of the examples, we briefly describe the typologies of data and tasks we use in our work.

10.1 Scope and Perspective

This chapter offers a view on geovisualization from the perspective of computer scientists with an extensive experience in developing software tools for exploratory analysis of spatial data. Our tools are mostly based on combination of familiar techniques from various disciplines: Cartography, Statistical Graphics, Information Visualization, and Human–Computer Interaction. Traditional mapping and graphing techniques are enhanced with interactivity and manipulability. Typically, the ideas concerning useful technique combinations and enhancements come to us when we examine some specific datasets received from people interested in exploring these data.

It is commonly recognized that techniques used for graphical representation of data must correspond to characteristics of the data (Bertin, 1983), and the same applies to software tools for visual data exploration. However, as we have learned from our

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

experience, the route from data characteristics to the development of appropriate tools consists of two parts: first, data characteristics determine the potential questions (tasks) that may emerge in the process of the data exploration; second, the tasks make requirements of the tools and thereby define the space of possible design options. In this chapter, we advocate the task – analytical approach to the selection of appropriate visualization techniques and design of tools for the exploratory analysis of geographically referenced data. For this purpose, we offer three examples of geovisualization tool design for different types of spatio-temporal data. Prior to the consideration of the examples, we introduce the typological framework we use for revealing the set of potential tasks from the characteristics of datasets to analyze. We hope this material will be useful both for designers of geovisualization tools and for analysts applying existing tools to their data.

10.2 Related Work

The large number of recently published papers and books combining in their titles the words "Geography" and "time" or their derivatives indicates the importance of temporal issues for contemporary geographic information science. It can be noted that most publications refer in this or that way to the same cardinal problem "How to make computers (or, more specifically, GIS) understand temporality and handle time-related information?" Various formal theories have been suggested that attempt to simulate human's understanding of time and (spatio-) temporal reasoning (Allen, 1984; Galton, 1987; Egenhofer and Al-Taha, 1992; Cohn et al., 1998; Frank, 1998). On this basis, different frameworks and methods for internal representation and operation of spatio-temporal data in databases and GIS are devised (Langran, 1992; Peuquet, 1994; 2002; Worboys, 1998; Wachowicz, 1999).

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

Our work on developing visualization-based exploratory tools was initially actuated by practical needs: we participated in several projects where different types of spatio-temporal data had to be sensibly presented to users. We studied the existing examples of geovisualization tools described in the literature (Kraak et al., 1997; Bloc et al., 1999; Fredrikson et al., 1999; Harrower et al., 2000; Oberholzer and Hurni, 2000; Slocum et al., 2000; and many others). Our attention was first attracted to the technique of map animation that can be found in almost all software systems for visualization of spatio-temporal data. However, we found soon that this technique in its "pure" form (i.e., playing a sequence of "snapshots" representing states of a phenomenon at successive moments of time) does not work as well for arbitrary data as it does in demonstrating evident trends like urban growth (Tobler, 1970). The main problem is that

preprint : November 2004 - do not redistribute.

animation does not give an analyst an opportunity to compare directly states at different moments in time. In order to detect and evaluate changes, she/he has to compare the state viewed at the current moment with mental images of earlier states. Investigation of temporal trends would require memorizing a large number of consecutive states. Hence, comparison and trend detection must be supported by other techniques, possibly, combined with animation.

We have failed to find a ready-to-use methodology for the design of geovisualization tools in the literature, i.e., a methodology that would link possible types of (spatio-temporal) data, possible types of questions about these data, or analytical tasks, and techniques that could support finding answers to these questions, although some systematization efforts have been undertaken by a number of researchers. Thus, one can find classifications of temporal maps on the basis of their contents (Muehrcke, 1978) or the methods of representing time (Kraak and MacEachren, 1994), consideration of "traditional" visual variables (Bertin, 1983), such as location, size, and color, from the perspective of their appropriateness for the representation of time (Kraak and MacEachren, 1994), and descriptions of new, "dynamic" variables, such as display date, frequency, and synchronization (DiBiase et al., 1992; MacEachren, 1995). Peuquet (2002) notes that this research is conducted within the paradigm of map semiotics, the original goal of which was to provide a set of rules for effective representation and communication of an intended "message". In data exploration, there is no message to be communicated, and hence, semiotic principles cannot be directly applied – they need to be extended or recast (Peuquet, 2002, p. 289–291). From our perspective, it is necessary to establish explicit links between visual and dynamic variables, on the one hand, and types of exploratory tasks on the other. Another shortcoming of this research is that it deals solely with representational forms and not interaction techniques.

Some work exists that considers particular types of interactive tools. Kraak et al. (1997) present a theoretical framework for the design of temporal legends for animated maps, and Edsall et al. (1997) make an attempt to relate three types of temporal legends (linear, cyclic, and textual) to different types of data (attribute changes vs. location changes) and temporal queries ("when?", "how long?", and "how fast?"). All these are valuable nuggets of a general design methodology, which is yet to be assembled. Meanwhile, the development of spatio-temporal geovisualization tools is largely an empirical endeavor supported by evaluation, for example, (see Fuhrmann et al., this volume (Chapter 28)).

In this chapter, we present a range of tools that we have designed for different types of data. The main purpose of the chapter is to demonstrate the interaction between data characteristics and the tasks that can emerge in data exploration, and the impact of these two factors on the requirements for visual data analysis tools that need to be developed. Although characteristics of the intended users are also one of the important factors affecting our work on tool development, a detailed consideration of this topic is beyond the scope of this chapter. After the description of each design example, we provide references to the literature describing other approaches to the visualization of similar data.

Prior to the description of the examples, we introduce the typologies of spatio-temporal data and analytical tasks we use in our work.

preprint : November 2004 - do not redistribute.

10.3 Typologies of Data and Tasks

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

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

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

Sometimes only one type of change takes place or is of interest to an analyst, but in many cases one needs to consider several types simultaneously.

In existential changes, further diversity is possible depending on whether the duration of events is significant or not. An analyst may treat events (e.g., earthquakes) as instant when duration of an event is negligibly short in comparison to the length of the time interval under analysis or when time of event appearance is important but not how long it lasts.

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

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

This classification parallels the notion of *question types* introduced by Bertin: "There are as many types of questions as components in the information" (Bertin, 1983, p. 10), the type being defined by what component is unknown. Such a component will be further referred to as "search target". Here we use the word "search" in

preprint : November 2004 - do not redistribute.

an abstract sense, which is different from the traditional usage of this term in Cartography or psychology for denoting only search in space.

A complementary division of questions proposed by Bertin is according to what he terms *levels of reading*: elementary, intermediate, and overall. Elementary questions refer to individual elements of data (e.g., individual places, time moments, and objects) while questions of the intermediate and overall levels address more general characteristics of a phenomenon (e.g., how it is distributed in space, how it behaves in time, or how characteristics are distributed over a set of objects). From our perspective, there is no principal difference between the intermediate and overall levels, as defined by Bertin. Both levels involve consideration of sets rather than individual elements. The difference is whether the whole set or its subsets are considered.

It should be noted that Bertin considered data in general, not specifically spatio-temporal data. Koussoulakou and Kraak (1992) demonstrate that in the specific case of spatio-temporal data, the distinction according to the reading levels can be independently applied to the spatial and to the temporal dimensions of the data. For example, the question "What is the trend of changing values at location l?" belongs to the elementary level in relation to the spatial component and to the overall level with respect to the temporal component. An analogous observation can be also made for the object dimension. Hence, each of the Peuquet's general question schemes of the form $A + B \rightarrow X$ (where A and B denote known, or given, data components and X stands for unknown information) can be further subdivided according to the level on which the known information is specified: elementary A and B, elementary A and overall/intermediate B, overall/intermediate A and elementary B, and overall/intermediate A and B.

MacEachren (1995) and Kraak et al. (1997) classify possible questions concerning spatio-temporal data into seven query types addressing the existence of an entity (if?), its location in time (when?), its duration (how long?), its temporal texture (how often?), its rate of change (how fast?), sequence of entities (what order?), and synchronization (do entities occur together?). These types can be viewed as an elaboration of a more general task "describe the times or set of times that a given object or set of objects occupied a given location or set of locations" (*where* + *what* → *when*) in the classification suggested by Peuquet.

While Bertin and Peuquet define possible information-seeking tasks in terms of components present in data, many researchers take another perspective by associating tasks with cognitive operations performed by a user. Different researchers consider quite diverse sets of cognitive operations, for example, Wehrend and Lewis (1990) distinguish eleven operations while Knapp (1995) suggests a set of four tasks: "identify", "locate", "compare", and "associate". It is not our goal to discuss and compare here all existing task typologies. We would only like to note that according to our observation, most of the "cognitive" task classifications implicitly involve differentiation of tasks on the basis of the search target and reading level. For example, identify differs from locate in the search target: in identify, the target is thematic characteristics of objects while in locate it is positions of objects in space and time; the task "distribution" from the classification of Wehrend and Lewis may be treated as identify or locate on the overall reading level.

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

For our purposes, we found it useful to distinguish between two basic cognitive operations, identify and compare, where compare means establishing relationships of various kinds (including temporal relationships) rather than just examining similarities and differences. In particular, compare subsumes such temporal queries as "in what order do entities appear?" (sequence) and "do entities occur together?" (synchronization) (MacEachren, 1995). We regard the distinction identify vs. compare as one more independent dimension of the task space in addition to the search target and reading level.

It should be further borne in mind that any general scheme acquires different shades of meaning when being applied to different types of spatio-temporal data. For example, when data about movement of discrete objects are analyzed, the three types of questions considered by Peuquet can be formulated as follows:

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

For data about changes of attributes of static spatial objects or locations (e.g., changes in population number and structure by municipalities of a country), the same schemes would be instantiated differently:

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

Hence, potential information-seeking tasks substantially interact with characteristics of data. As a result, a tool designer needs to define the set of possible tasks individually for each particular type of data, possibly by adopting and adapting some general typology. In the remaining part of the chapter, we are going to demonstrate through a few specific examples of different spatio-temporal data, ways in which a designer analyzes data characteristics in order to determine possible types of questions that may arise and how this guides the choice of appropriate exploratory techniques to suggest to the users.

10.4 Time Controls and Dynamic Map Display

Despite the variety of spatio-temporal data, there are some general techniques applicable to all data types. Specifically, the spatial aspect of data is typically visualized with the use of maps, as they are well suited to conveying spatial information through human vision. Therefore, all our exploratory tools involve interactive map displays. For dealing with the temporal dimension of data, we have developed the time manager – an assembly of interactive widgets connected to a map display. These widgets are similar to those available in most of the systems supporting map animation. In particular, the time manager includes VCR-style buttons for starting and stopping animation and "stepping"

preprint : November 2004 - do not redistribute.

through time. In addition to the standard functions, however, the time manager allows the user to choose between the instant view (the map represents the state of the world at a selected moment) and the interval view (the map represents events, movements, etc., that occurred during a selected interval). Both views can be combined with animation. In the interval view, the interval of the user-selected length will be shifted along the time axis by the specified number of time units on each step of the animation.

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

10.5 Visualization of Instant Events

Within the project "NaturDetektive" (NaturDetektive, 2003), schoolchildren from all over Germany registered through the Internet their observations of nature, specifically, when and where they had noticed a certain plant or bird. For some plants, the children had to distinguish different stages of development: appearance of first leaves, beginning of blossoming, or appearance of fruits. Our task in the project was to design and implement methods for visualization of the collected data that could be used, on the one hand in schools for educational purposes, and on the other hand, by project managers and interested public to examine children's involvement in the project.

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

1. Elementary level (with respect to time):

   - What species were observed, and in which states, at the moment *t* around the location l/in the area a? What species and states were predominantly observed over the whole territory at the moment *t*? Are there any differences in the variety of species observed in the north and in the south? etc.
   - Where was the species s (in the state s′) observed at the moment *t*? What was the spatial distribution of observations of the species s at the moment *t*?
   - When was the species s (in the state s′) observed around the location l/in the area a? When did the largest number of observations of the species s occur?
   - What are attributes of a particular observation, e.g., who made it, when, in what environment, etc.?

2. Intermediate/overall level (with respect to time):

   - How did the variety of species observed at the location l/in the area a/over the whole territory change over time?
   - How did the occurrences of the species s (in the state s′) at the location l/in the area a vary over the time? How did the spatial distribution of observations of the species s change over the time?

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

- What is the spatio-temporal behavior of the species s (i.e., when does it/its different stages appear in different parts of Germany, how long are the intervals between appearing of different stages, etc.)?

From the analysis of the possible questions we saw, first of all, the necessity of visual discrimination of observations of different species. Therefore, we chose to visualize the data on the map using iconic symbols with the shapes resembling the appearance of the species (Figure 10.1a). Variation of icon colors was used for representing different stages of plant development.

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

- Selection of specific time moments (supported by the time manager).
- Focusing on particular locations or areas (supported by map zooming and panning facilities).
- Selection of a particular species. For this purpose we implemented a "species toolbar" in which the users can either choose one of the species (in this case the icons of the other species are hidden) or all the species at once. The second mode allows the users to study the total variety of species and its development over time.
- Access to information about a particular observation. To support this operation, we implemented a lookup interface that requires the user just to point with the mouse at the corresponding icon. All the information about this observation (date, species, state of development, and who made the observation) will be shown in a popup window (Figure 10.1a). An observation record may have a reference to a URL where additional information about the species or/and the observer is given. This URL is opened when the user clicks on the icon.
- Observing changes over time. This operation is done using map animation controlled through the time manager. The animation allows the user to investigate, on the one hand, evolution of the variety of species or the spatio-temporal behavior of a particular species, on the other hand, how participation of the schoolchildren in the project developed over time.

Taking into account that the tool was intended for schoolchildren, we implemented a simplified version of the time manager, which can be seen in Figure 10.1a on the right of the map below the legend. With this version, it is possible to select time moments (by clicking on the slider bar or entering dates in the text field) as well as start (resume) and stop the animation. However, if the user presses the button "Erweitert" ("Extended"), the time manager turns to its normal form providing more sophisticated operations (Figure 10.1b). The user can return back to the simple version by pressing the button "Simplifiziert" ("Simplified").

Although the resulting tool allows comparisons of different areas and distributions of observations of different species to be made, it does not support comparison of different time moments. For the latter purpose, one could suggest using two (or even more) parallel map displays. Another opportunity is to represent "older" events on the map in a specific way, for example, by "dimmed" icons. However, in this

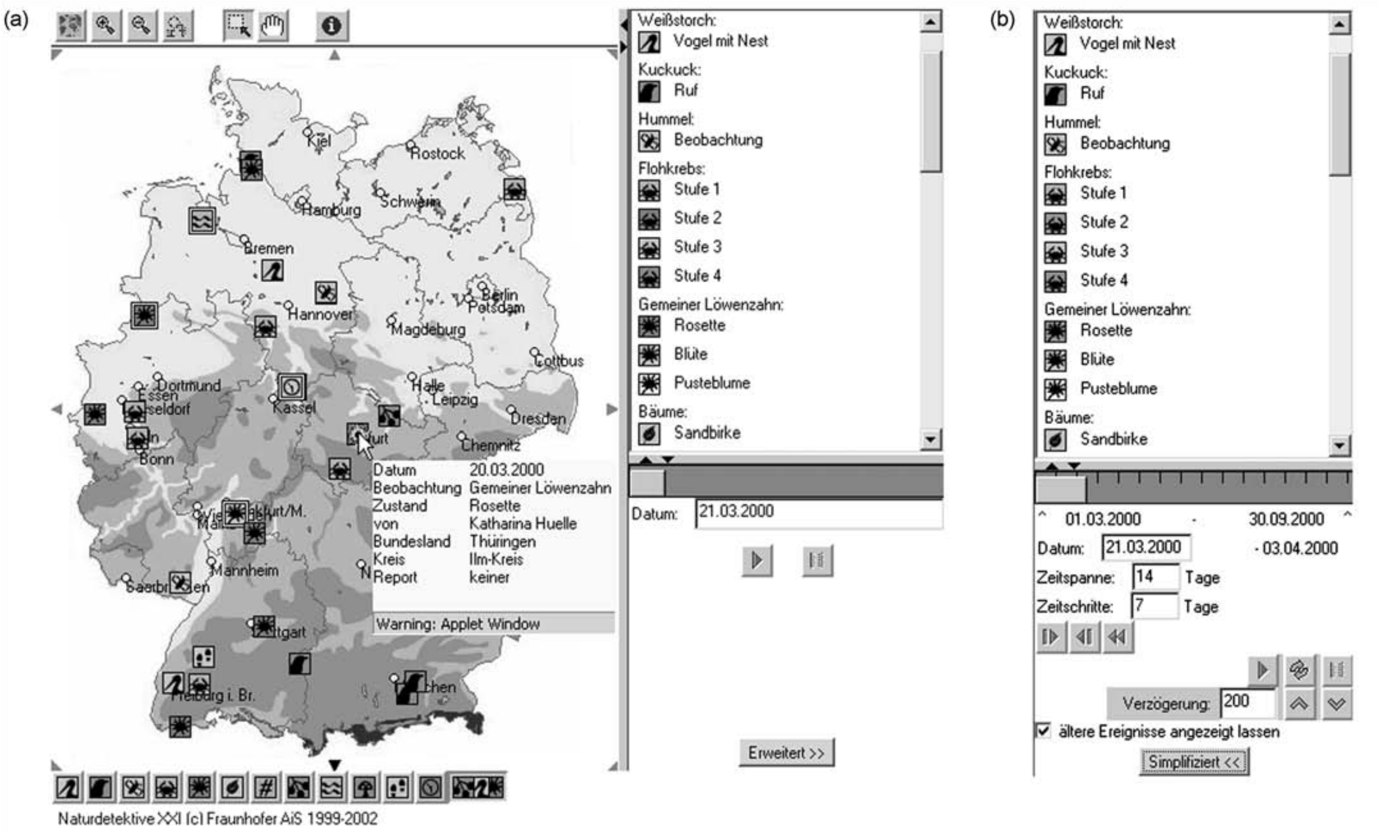

Figure 10.1. Visualization of nature observations. The time manager initially appears in its simplified form shown in the lower right corner of Figure 10.1a. Figure 10.1b shows the appearance of the time manager after pressing the button "Erweitert ≫" (Extended).

particular case, we preferred to avoid further complication of the tool since it was intended first of all for children. For the same reason, we did not initially enable selection of arbitrary combinations of species through the "species bar". However, as the Naturdetektive project continued, we received a request from the organizers to add this opportunity and implemented it in a later version of the tool. Another improvement concerns dealing with overlapping symbols. In the latest version, when several symbols have close locations, they are replaced by a special "stack" symbol. Clicking on this symbol displays the list of observations it represents, and the user can select any of them for viewing the details. Unfortunately, the project organizers insisted on changing the method of depicting observations to using differently colored rectangular frames with numbers inside them instead of the iconic symbols. As a result, it has become hard to distinguish different species and states on the map. Therefore, we preferred to illustrate here with screenshots from the older version of the software.

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

Various other approaches to the visualization of events exist. The SpaTemp system (Stojanovic et al., 1999) combines computer-oriented techniques for visualizing events with traditional cartographic representation methods. In particular, the system can show the time that an event commences or the period of its existence through labels. The "age" of events may be represented by variation of colors. Fredrikson et al. (1999) describe, by example of traffic incidents, how data about events can be explored using various forms 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. Thus, summary data about spatially aggregated events (e.g., by road sections) are shown on an interactive map by symbols the size of which is proportional to the number of events. In our system CommonGIS, we apply the space–time cube technique (MacEachren, 1995), with the horizontal dimensions representing the geographical space and the vertical dimension representing time. Events are positioned in the 3D space according to their geographical locations and the times of appearance, for example, (see Mountain, this volume (Chapter 9)).

Changes in the observed variety of species over time summarized over the whole territory or over selected regions could be represented using the "Theme River" technique (Havre et al., 2002).

10.6 Visualization of Object Movement

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

- Where was each object at a selected moment *t*?
- When did a particular object o visit the location l?

preprint : November 2004 - do not redistribute.

- How long did it stay at this location?
- How did the positions of objects change from moment t_1 to moment t_2?
- What were the trajectories of the objects during the interval (t_1, t_2)?
- What was the speed of movement during the interval (t_1, t_2)?
- How did the speed of movement change over time or with respect to spatial position?

The telemetric observations recording the migration of white storks to Africa in autumn and back to Europe in spring are example of data recording moving objects. For identifying and comparing trajectories, it is convenient to have the paths represented on a map by lines or arrows. However, static representation of trajectories is not appropriate for exploration of the speed of movement. Besides, 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.
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 entire routes are visible.
3. "Time window": the map shows the fragments of the routes made during the time interval of a specified length.

Our tool enables all three variants of animation. In our experiments, we found that the variant "snapshot in time" is suitable for exploring movement of a single object. With several objects, however, it is 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 losing track. However, after several steps of animation, the "tails" representing past movements often 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. The time window mode proved to be the most convenient for exploration and comparison of object behaviors in terms of the speed of movement. In this mode (Figure 10.2), arrow chains moving over the map represent path fragments made during time intervals of a constant length. 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 is motionless, staying for some time in the same place, the corresponding chain reduces to a single dot. By varying the length of the time window, it is possible to explore complex trajectories.

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

Figure 10.2. The time window technique for animating 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 (white storks) during 5 days. In the second and subsequent screenshots, the time window is shifted by one day forward relative to the preceding image. Note that movements of a particular bird did not necessarily occur every day.

We invite the readers to explore the movement of the storks by running the Java applet that is available online (Andrienko and Andrienko, 2003). A more detailed description and color illustrations can be found in Andrienko et al. (2000a,b).

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

When we built the tool, migration data for just one year were available. Since then, more data have been collected, and now there is an opportunity to compare migrations in different years. Therefore, we are currently working on extending the tool so that such comparisons become possible.

Various other approaches to the visualization of object movement exist. MacEachren (1995) and Peuquet and Kraak (2002) suggest that trajectories of object movement can be represented using the technique of the space–time cube. According to this technique, points in 3D 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 online (Kraak, Undated). This technique, however, seems unsuitable for exploring the movement of multiple objects. Mountain and Raper (2001a,b) and Mountain and Dykes (2002) describe a software program called location trends extractor, or LTE, for analysis of routes. LTE represents a trajectory on a spatial display as a sequence of points colored according to the time when the corresponding locations were visited. Simultaneously, the data are summarized on a temporal histogram, which shows the number of visited locations by time intervals. The user can focus the analysis on interactively selected data subsets by applying spatial, temporal, or attribute selection criteria. LTE includes various computational procedures for analyzing route data, e.g., for breaking the movement history into periods of homogeneous behavior, revealing rapid changes in direction or speed, identifying places of interest, etc. The software was designed for analyzing

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

the movement of single objects through time and space, rather than comparing multiple trajectories. Wilkinson (1999) describes how data about butterfly migration can be represented on a map using the SYSTAT graphics package.

10.7 Visualization of Changing Thematic Data

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

In the two applications described above, it was possible to show data for several different time moments on a single map. This created good opportunities for comparisons, detecting changes, and estimating the degrees of changes. With this particular data type, such combination is rather difficult since at each moment the objects cover the whole territory. A possible technique for representing data related to several moments on the same map would be drawing a bar chart (sequence of bars) in each area with heights of the bars proportional to the values of the attribute at these moments in this area. Such a map is convenient for examining changes of the attribute values in each particular area. However, it is unsuitable for considering the distribution of attribute values over the territory at any particular moment and for observing changes of the distribution over time.

An overall view of a territory is well supported by the cartographic presentation method called the choropleth map. According to this method, the contour of each geographic object is filled with some color, the intensity of which encodes the magnitude of the value of the attribute. We combined this representation method with time controls and received a dynamic choropleth map display (Figure 10.3). This display provides a good overall view of the spatial distribution of attribute values at a selected time moment and dynamically changes when another moment is chosen, in particular, in the course of animation.

However, the choropleth map is poorly suited for the tasks of estimating changes and trends occurring in each particular area and is even less appropriate for comparing changes and trends occurring in different areas. Therefore, we found it necessary to complement the dynamic map with an additional non-cartographic display, a time plot, showing the temporal variation of attribute values for each area (shown at the bottom of Figure 10.3). The technique of time plot is widely used in statistics. The *X*-axis of the plot represents the time, and the *Y*-axis – the value range of the attribute. The lines connect positions corresponding to values of the attribute for the same area at successive time moments. Like a map with bar charts, the time plot is good for examining dynamics of values for each individual object. In addition, it supports comparison of value variations for two or more objects and the detection of objects with outstanding behaviors (in terms of the variation of attribute values) much more successfully than a chart map.

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

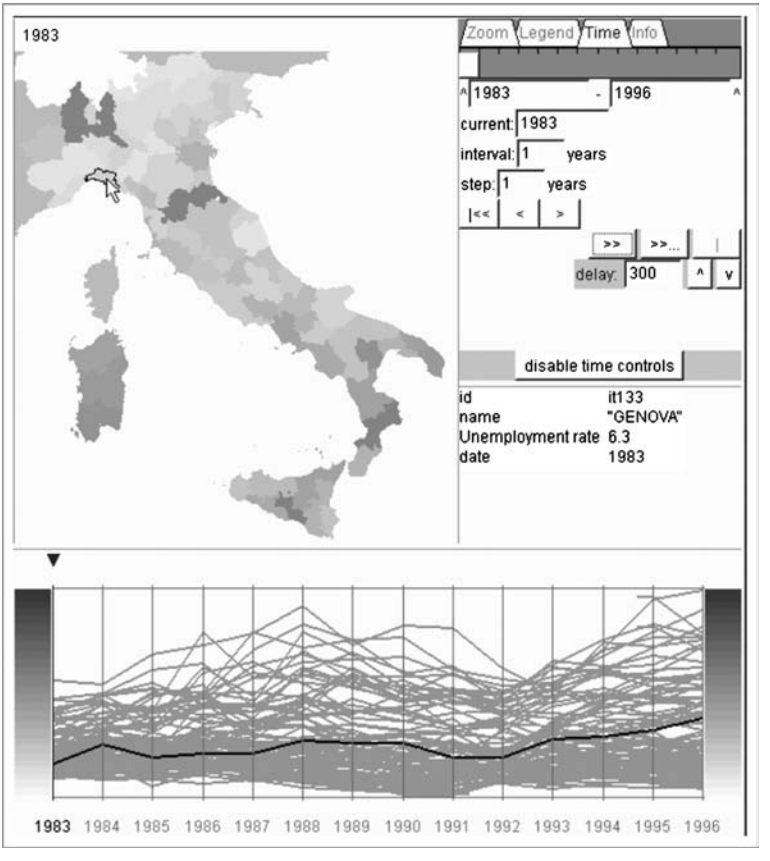

Figure 10.3. An interactive time-series plot dynamically linked to a map. Highlighted in the graph is the line corresponding to the municipality of Genoa, which is pointed to on the map by the cursor.

The earliest combination of a map with a time plot was Minard's famous presentation of Napoleon's campaign in Russia (described, for example, in Tufte (1983)). 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. Thus, in our implementation, the time plot is sensitive to mouse movement: it highlights the line or bundle of lines pointed to with the mouse. Simultaneously, the corresponding objects are highlighted in the map. The link works also in the opposite direction: pointing to any object in the map results in the corresponding line being highlighted in the time plot (Figure 10.3). So, the map serves as a "visual index" to the plot making it easy for the user to focus on any particular object for considering dynamics of its characteristics with the use of the plot. And vice versa, it is easy to determine which object corresponds to any particular behavior that attracted the analyst's attention. Due to its interactivity and dynamic link to the map, the time plot is a useful analysis tool even despite the lines

preprint : November 2004 - do not redistribute.

overlapping and being cluttered: highlighted lines are clearly visible, and the remaining lines provide a useful context for comparing the object(s) in focus with the other objects. Besides, it is possible to switch the display to the mode when only selected lines are visible. Furthermore, the time plot may be zoomed in the horizontal and vertical dimensions, also reducing line overlap.

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

- with the values for the previous time moment;
- with the values for a selected fixed moment;
- with the value for a selected object;
- with a constant reference value.

In the comparison mode, the map represents changes (computed absolute or relative differences between values) rather than the initial attribute values. This technique is known from Cartography as "change map". We represent the results of computations using a bi-directional color scheme (Brewer, 1994): shades of two different colors represent values higher and lower than the current reference value. The degree of darkness shows the amount of difference between the represented value and the reference value. White coloring is used for objects with values exactly equal to the reference value.

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

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

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

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

As the user chooses the comparison mode and applies various variants of comparison, the time plot changes in accord with the map. Initially the time plot shows the source data, i.e., values of the explored attribute at each time moment. In the comparison mode it switches to displaying the results of subtraction of the reference values from the source values (absolute difference) or division of source values by the reference values (relative difference). Figure 10.4 demonstrates how the time plot from Figure 10.3 looks in different comparison modes. All four screenshots represent absolute differences.

We continue to develop the tool described here. In particular, we are implementing temporal aggregation of numeric attribute data. The system will calculate and visualize on the map and on the time plot various summary statistics of data on intervals of a user-specified length: mean, median, minimum, maximum values, etc. In particular, averaging values on intervals will result in smoothing the time plot, which can help in the trend analysis. In the comparison mode, the aggregation will be applied to the calculated values.

Various other approaches to visualizing thematic changes exist. Change maps, i.e., maps representing for each location or area the absolute or relative amount of change between two time moments, are known in traditional Cartography and used in other software systems, for example, Atlas of Switzerland (Oberholzer and Hurni, 2000) and MapTime (Slocum et al., 2000). In these two systems, it is also possible to analyze the variation of attribute values by comparing several maps corresponding to different time moments. The same technique is used in the Cancer Mortality Maps & Graphs of the USA National Cancer Institute (National Cancer Institute, 2003); however, here the data are aggregated by time intervals with the minimum length of 5 years. It is also possible to view the aggregated data on an animated map display.

In addition to displaying data on maps, some software packages, for example, TEMPEST (Edsall and Peuquet, 1997) and STEM (Morris et al., 2000), can show temporal variation of numeric attribute values at selected locations on a time-series graph; however, these examples offer no dynamic link between the maps and graphs. Hochheiser and Shneiderman (2001) suggest sophisticated interactive tools for data exploration with an interactive time-series graph that being combined with a map display, would also be very useful for exploring spatio-temporal data.

Analysis of temporal variation of numeric variables (attributes) is one of the most important research topics in statistics, and it is not surprising that statisticians are undertaking significant research work on visualization and analysis of spatio-temporal data. Thus, Unwin and Wills (1998) show how time-series data can be analyzed using interactive, transformable time plots (although not linked to maps). Carr et al. (1998) suggest the visualization method called Linked Micromaps. The method is based on dividing the set of geographical objects into small groups. Each group is represented on a separate small map accompanied by a statistical display, which may contain, in particular, time-series plots or box plots summarizing the value distribution over the whole time period. Mockus (1998) describes a tool consisting of a map view and a so-called Aggregation Eye, which allows the user to interactively select time intervals and ranges of attribute values. As a result, the data satisfying the query are aggregated and shown in the map using symbols varying in size. Alternatively, it is possible to display attribute

preprint : November 2004 - do not redistribute.

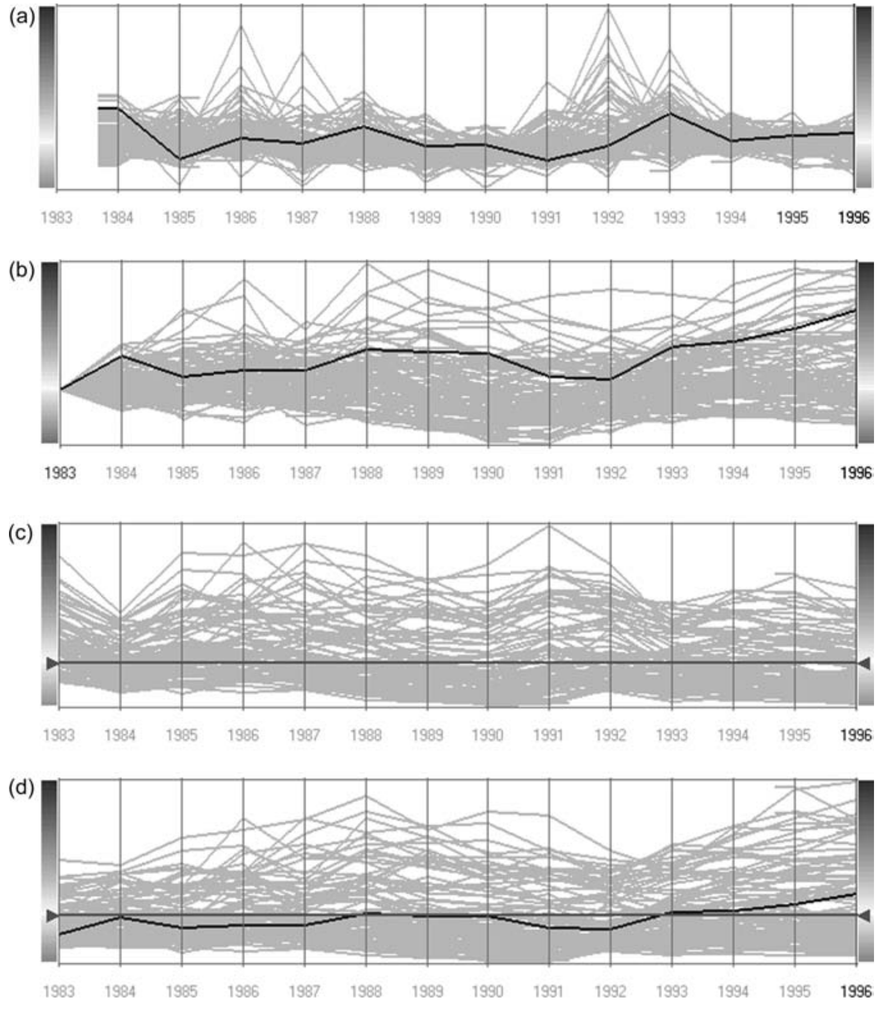

Figure 10.4. Transformations of the time plot from Figure 10.3 in different comparison modes: (a) with the previous moment; (b) with a fixed moment, specifically, with the year 1983; (c) with a selected object, specifically, Genoa; (d) with a selected value, specifically, 10%. In all the screenshots, the line for Genoa is highlighted. In Figure 10.4d, the highlighted straight line corresponds to the selected value of 10%.

variation by line plots drawn at the corresponding locations on the map. Eddy and Mockus (1994) apply spatial and temporal data smoothing for building animated map visualization.

10.8 Conclusion

Visual exploration of spatio-temporal data requires tools that can help users find answers to different types of questions that may arise in relation to such data. In this

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

chapter, we have shown that the questions an analyst is likely to be concerned with are closely related to the characteristics of data under analysis. Therefore, different sets of exploratory techniques are needed for different types of spatio-temporal data. We have considered three different types of data: instant events, object movement, and changing thematic characteristics of static spatial objects. We have described how we designed visualization tools to support exploratory analysis of each type of data. Thus, in analysis of movement the time window technique showing trajectory fragments made during intervals of a constant length is particularly productive. Various methods of data transformation and combination of a dynamic map display with a time-series plot are useful for analysis of thematic data associated with area objects. The time plot can also be recommended for representing calculated statistics for other types of spatio-temporal data, such as numbers of events or traveled distances.

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

It can be noted that the tools we implement are mostly based on combination of familiar mapping and graphing techniques, which are enhanced with interactivity and manipulability. A tool may consist of several complementary data displays that are tightly linked in such a way that one display immediately reacts to user's actions in another display. A great flexibility in creating various technique combinations for different purposes (depending on data, tasks, and user requirements) can be achieved if each visualization technique is implemented as a component that can be included or removed without requiring any changes in the other parts of the system. Our system CommonGIS, which includes numerous visualization tools, is built according to this principle. The system has a centralized architecture: the tight linking of components is provided by the system's core, which propagates various events among the components attached to it. Hence, each component does not need to "know" about the other components. Another approach is implemented in GeoVISTA *Studio* (Takatsuka and Gahegan, 2001), where the components are autonomous and can be combined by explicitly linking their inputs and outputs using a graphical configuration tool. An alternative and comprehensive Java-based software development kit for data visualization called nViZn is now commercially available from SPSS Inc. The underlying ideas are described by Wilkinson et al. (2000, 2001). Such developments offer clear opportunities for creating flexible and usable visualization tools. The argument presented here is that data and task-driven approaches to designing and developing tools that draw upon these technologies will result in the most effective instruments for those investigating spatio-temporal phenomena. Doing so will enable us to develop an appropriate theoretical and methodological context for geovisualization.

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4

preprint : November 2004 - do not redistribute.

Acknowledgements

The development of the techniques and tools for visual exploration of time-variant spatial data was partly undertaken within the project EuroFigures ("Digital Portrait of the EU's General Statistics", Eurostat SUPCOM 97, Project 13648, Subcontract to JRC 15089-1999-06) and is currently a part of the project SPIN ("Spatial Mining for Data of Public Interest", IST Program, project No. IST-1999-10536). We are grateful to Prof. Alan MacEachren for valuable comments on the early versions of the chapter.

References

Allen, J. F., (1984) "Toward a general theory of action and time", *Artificial Intelligence*, 23(2), 123-154.

Andrienko, G., and Andrienko, N., (2003) *Seasonal Migration of White Storks, 1998–1999*. Online: http://www.ais.fhg.de/and/java/birds/ (03/10/02).

Andrienko, N., Andrienko, G., and Gatalsky, P., (2000a) "Supporting visual exploration of object movement", *Proceedings of the Working Conference on Advanced Visual Interfaces AVI 2000,* Palermo, Italy, pp. 217-220.

Andrienko, N., Andrienko, G., and Gatalsky, P., (2000b) "Towards exploratory visualization of spatio-temporal data", *Proceedings of the 3rd Agile Conference on Geographic Information Science,* Helsinki.

Bertin, J., (1983) *Semiology of Graphics: Diagrams, Networks, Maps*. Madison, Wisconsin: University of Wisconsin Press.

Bloc, C., Koebben, B., Cheng, T., and Kuterema, A. A., (1999) "Visualization of relationships between spatial patterns in time by cartographic animation", *Cartography and Geographic Information Science*, 26(2), 139-151.

Bloc, C., (2000) "Monitoring Change: characteristics of dynamic geo-spatial phenomena for visual exploration", In: Freska, Ch., et al., (eds.), *Spatial Cognition*, LNAI 1849. Berlin, Heidelberg: Springer-Verlag, pp. 16-30.

Brewer, C. A., (1994) "Color use guidelines for mapping and visualization", In: MacEachren, A. M., and Taylor, D. R. F., (eds.), *Visualization in Modern Cartography*. Vol. 2. Oxford: Elsevier Science Ltd, pp. 123-148.

Carr, D. B., Olsen, A. R., Courbois, J. P., Pierson, S. M., and Carr, D. A., (1998) "Linked micromap plots: named and described", *Statistical Computing and Statistical Graphics*, Newsletter, 9(1), 24-32.

Cohn, A. G., Gotts, N. M., Cul, Z., Randell, D. A., Bennett, B., and Gooday, J. M., (1998) "Exploiting temporal continuing qualitative spatial calculi", In: Egenhofer, M. J., and Golledge, R. G., (eds.), *Spatial and Temporal Reasoning in Geographic Information Systems*. New York, Oxford: Oxford University Press, pp. 5-24.

DiBiase, D., MacEachren, A. M., Krygier, J. B., and Reeves, C., (1992) "Animation and the role of map design in scientific visualization", *Cartography and Geographic Information Systems*, 19(4), 201-214, see also pp. 265-266.

preprint : November 2004 - do not redistribute.

Eddy, W. F., and Mockus, A., (1994) “An example of the estimation and display of a smoothly varying function of time and space - the incidence of mumps disease”, *Journal of the American Society for Information Science*, 45(9), 686-693.

Edsall, R., and Peuquet, D., (1997) “A graphical user interface for the integration of time into GIS”, *Proceedings of the 1997 American Congress of Surveying and Mapping Annual Convention and Exhibition,* Seattle, WA, pp. 182–189.

Edsall, R. M., Kraak, M. J., MacEachren, A. M., and Peuquet, D. J., (1997) “Assessing the effectiveness of temporal legends in environmental visualization”, *GIS/LIS’97,* Cincinnati, Oct. 28–30, pp. 677-685.

Egenhofer, M. J., and Al-Taha, K. K., (1992) “Reasoning about gradual changes of topological relationships”, In: Frank, A. U., Campari, I., and Formentini, U., (eds.), *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, Lecture Notes in Computer Science, Vol. 693. Berlin: Springer-Verlag, pp. 196-219.

Frank, A. U., (1998) “Different types of “Times” in GIS”, In: Egenhofer, M. J., and Golledge, R. G., (eds.), *Spatial and Temporal Reasoning in Geographic Information Systems*. New York: Oxford University Press, pp. 40-62.

Fredrikson, A., North, C., Plaisant, C., and Shneiderman, B., (1999) “Temporal, geographic and categorical aggregations viewed through coordinated displays: a case study with highway incident data”, *Proceedings of Workshop on New Paradigms in Information Visualization and Manipulation (NPIVM’99)*. New York: ACM Press, pp. 26-34.

Galton, A. P., (1987) *Temporal Logics and Their Applications*. San Diego: Academic Press.

Harrower, M., MacEachren, A. M., and Griffin, A. L., (2000) “Developing a geographic visualization tool to support earth science learning”, *Cartography and Geographic Information Science*, 27(4), 279-293.

Havre, S., Hetzler, E., Whitney, P., and Nowell, L., (2002) “ThemeRiver: visualizing thematic changes in large document collections”, *IEEE Transactions on Visualization and Computer Graphics*, 8(1), 9-20.

Hochheiser, H. and Shneiderman, B., (2001) Visual Specification of Queries for Finding Patterns in Time-Series Data, *Technical Report #CS-TR-4326. UMIACS-TR-2001-25*, University of Maryland, Computer Science Dept.

Knapp, L., (1995) “A task analysis approach to the visualization of geographic data”, In: Nyerges, T. L., Mark, D. M., Laurini, R., and Egenhofer, M. J., (eds.), *Cognitive Aspects of Human–Computer Interaction for Geographic Information Systems*. Dordrecht: Kluwer Academic, pp. 355-371.

Koussoulakou, A., and Kraak, M. J., (1992) “Spatio-temporal maps and cartographic communication”, *The Cartographic Journal*, 29, 101-108.

Kraak, M. J., (undated) *Minard—What Has Been Done by ITC?*. Online: http://www.itc.nl/personal/kraak/1812/minard-itc.htm (23/10/03).

Kraak, M. J., and MacEachren, A. M., (1994) “Visualization of the temporal component of spatial data”, In: Waugh, T., and Healey, R., (eds.), *Proceedings of the Sixth International Symposium on Spatial Data Handling, Advances in GIS Research,* Edinburgh, Scotland, pp. 391-409.

preprint : November 2004 - do not redistribute.

Kraak, M. J., Edsall, R. M., and MacEachren, A. M., (1997) “Cartographic animation and legends for temporal maps: exploration and or interaction”, *Proceedings 18th International Cartographic Conference,* Stockholm, June 23–27, 1997, IGU, pp. 253-262.

Langran, G., (1992) *Time in Geographic Information Systems*. London: Taylor and Francis.

MacEachren, A. M., (1994a) *Some Truth with Maps: A Primer on Symbolization and Design*. Washington: Association of American Geographers.

MacEachren, A. M., (1994b) “Time as a cartographic variable”, In: Hearnshaw, H., and Unwin, D., (eds.), *Visualization in Geographical Information Systems*. Chichester: Wiley, pp. 115-130.

MacEachren, A. M., (1994c) “Visualization in modern cartography: Setting the agenda”, In: MacEachren, A. M., and Taylor, D. R. F., (eds.), *Visualization in Modern Cartography*. Oxford: Pergamon, pp. 1-12.

MacEachren, A. M., (1995) *How Maps Work: Representation, Visualization, and Design*. New York: The Guildford Press, p. 513.

MacEachren, A. M., and Kraak, M. J., (1997) “Exploratory cartographic visualization: advancing the agenda”, *Computers & Geosciences*, 23(4), 335-344.

Mockus, A., (1998) “Navigating aggregation spaces”, *IEEE Information Visualization Symposium 1998 Late Breaking Hot Topics Proceedings*. Research Triangle Park, NC: IEEE Computer Society Press, pp. 29-32.

Morris, K., Hill, D., and Moore, T., (2000) “Integrated data management and visualization through space and time”, In: Fullerton, K., (ed.), *Proceedings of 5th EC-GIS Workshop,* 28–30 June 1999. Stresa, Italy: EUR 19018 EN, European Communities, pp. 460-473.

Mountain, D., and Dykes, J., (2002) “What I did on my vacation: spatio-temporal log analysis with interactive graphics and morphometric surface derivatives”, *Proceedings of GISRUK’2002,* University of Sheffield, April 2003.

Mountain, D., and Raper, J., (2001a) “Modelling human spatio-temporal behaviour: a challenge for location-based services”, *Geocomputation’2001 – 6th International Conference on Geocomputation,* University of Queensland, Australia, September 2001.

Mountain, D., and Raper, J., (2001b) “Positioning techniques for location-based services: characteristics and limitations of proposed solutions”, *Aslib Proceedings*, 53(10), 404-412.

National Cancer Institute, (2003) *Cancer Mortality Maps and Graphs.* Online: http://www3.cancer.gov/atlasplus/(23/10/03).

NaturDetektive (2003) Naturdetektive 2003. Online: http://www.naturdetektive.de (23/10/03).

Oberholzer, C., and Hurni, L., (2000) “Visualization of change in the interactive multimedia atlas of Switzerland”, *Computers & Geosciences*, 26(1), 423-435.

Peuquet, D. J., (1994) “Its about time: a conceptual framework for the representation of temporal dynamics in geographic information systems”, *Annals of the Association of American Geographers*, 84(3), 441-461.

preprint : November 2004 - do not redistribute.

Peuquet, D., (2002) *Representations of Space and Time*. New York: Guilford, p. 379.

Peuquet, D. J., and Kraak, M. J., (2002) "Geobrowsing: creative thinking and knowledge discovery using geographic visualization", *Information Visualization*, 1, 80-91.

Seasonal Migration of White Storks, (2003). *Seasonal Migration of White Storks,* 1998–1999. http://www.ais.fraunhofer.de/and/java/birds

Slocum, T., Yoder, S., Kessler, F., and Sluter, R., (2000) "MapTime: software for exploring spatiotemporal data associated with point locations", *Cartographica*, 37(1), 15-31.

Stojanovic, D., Djordjevic-Kajan, S., Mitrovic, A., and Stojanovic, Z., (1999) "Cartographic visualization and animation of the dynamic geographic processes and phenomena", *Proceedings of 19th International Cartographic Conference*, pp. 739-746.

Takatsuka, M., and Gahegan, M., (2001) "Sharing exploratory geospatial analysis and decision making using GeoVISTA *Studio*: from a desktop to the web", *Journal of Geographic Information and Decision Analysis*, 5(2), 129-139.

Tobler, W., (1970) "A computer movie simulating urban growth in the Detroit region", *Economic Geography*, 46(2), 234-240.

Tufte, E. R., (1983) *The Visual Display of Quantitative Information*. Cheshire, CT: Graphics Press, p. 197.

Unwin, A., and Wills, G., (1998) "Exploring time series graphically", *Statistical Computing and Graphics Newsletter*, 2, 13-15.

Wachowicz, M., (1999) *Object-Oriented Design for Temporal GIS*. London: Taylor and Francis.

Wehrend, S., and Lewis, C., (1990) "A problem-oriented classification of visualization techniques", *Proceedings of the First IEEE Conference on Visualization: Visualization'90,* October 1990. Los Alamitos, CA: IEEE, pp. 139-143.

Wilkinson, L., (1999) *The Grammar of Graphics*. New York: Springer-Verlag.

Wilkinson, L., Rope, D. J., Carr, D. B., and Rubin, M. A., (2000) "The language of graphics", *Journal of Computational and Graphical Statistics*, 9(3), 530-543.

Wilkinson, L., Rope, D. J., Rubin, M. A., and Norton, A., (2001) "nVizn: an algebra-based visualization system", *Proceedings of the 1st International Symposium on Smart Graphics,* March 21–23, 2001. New York: Hawthorne, pp. 76–82.

Worboys, M. F., (1998) "A generic model for spatio-bitemporal geographic information", In: Egenhofer, M. J., and Golledge, R. G., (eds.), *Spatial and Temporal Reasoning in Geographic Information Systems*. New York: Oxford University Press, pp. 25-39.

J. Dykes, A.M. MacEachren, M-J. Kraak (2005), Exploring Geovisualization, Pergamon, 732pp. 0-08-044531-4