

CHAPTER 42

Interactive Maps for Exploring Spatial Data

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42.1 Introduction

A hallmark of modern geographic information system (GIS) software is its capability for user interaction. Interactivity—referring here to the myriad ways that a system, or data represented in a system, can change according to user input—is now ubiquitous enough in computerized information systems that it is often taken for granted. However, interactivity should be examined critically in the context of maps and geographic representations in order to understand how far GIS has come in facilitating data analysis, and what might still be developed in order to examine data sets that are presently difficult to examine given the state-of-the-art of GIS. This chapter explores the design and use of interactive maps for spatial data exploration and analysis, paying particular attention to applications incorporating approaches from cartography, statistics and computer science. We also consider the role of the interactive capabilities and potential of GIS for the burgeoning field of visual analytics, and look ahead to the possibilities of incorporating interaction into future designs of GIS, in particular those that can handle spatiotemporal data. Present GISs, with their unique and highly interactive interfaces, are well-designed for many spatial data exploration tasks. However, developers and users should consider implementing modes of interaction not presently enabled in GIS that would facilitate a wider range of geographic visualization and analysis. We thus advocate the increase of interactive capabilities for map products created in a GIS environment based on the improvements for data exploration that could be gained.

42.2 Interaction and Geo-visualization

Traditional maps are designed by cartographers to communicate information to a map user or group of map users. The incorporation of interactivity into maps allows for this same communication between cartographer and map user, but it also affords a dialogue of sorts between the representation and the user, as the map user becomes an important agent in the creation and re-presentation of the information. In the days before users were given opportunities to interact with maps, the process of cartography was a one-way path that led from “reality” through several intermediate steps—the cartographer’s filtering of that reality (tempered by his or her own intentional or unintentional bias), selection, generalization, symbolization, the user’s perception of the map, and a (potential) alteration of the user’s mental model of the represented phenomenon (Figure 42-1) (Robinson et al. 1995; MacEachren 1995). The provision of interactivity adds an important feedback to this process: though the user cannot alter reality itself, every other step of the cartographic process can be subject to alteration with an interactive map. User interaction can alter the themes and base map information that are displayed, the scale and aggregation of the data, the level of detail, the type of map, the classification, the color scheme, the viewing angle, the highlighted elements—interactive maps afford a user an infinite number of representation possibilities, each with the potential to alter mental models and to construct knowledge in a unique way (Figure 42-2).

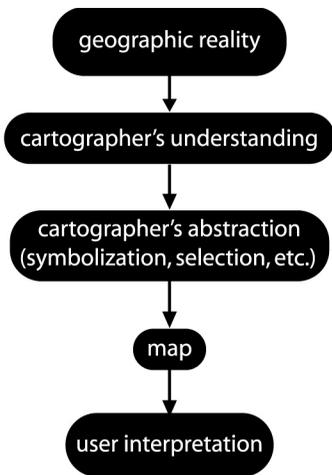


Figure 42-1 Typical model of cartographic communication.

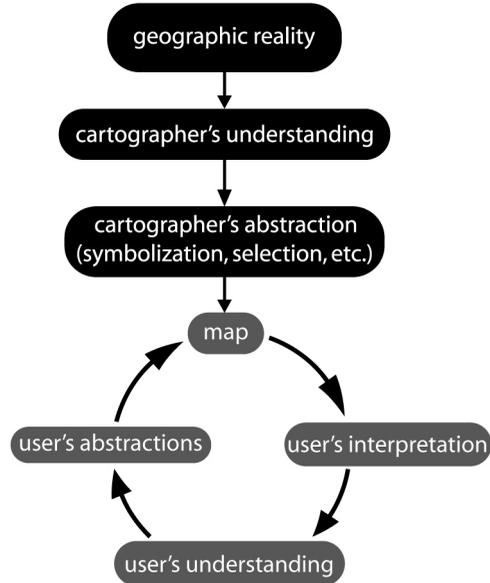


Figure 42-2 Interaction allows a user of a map to incorporate his/her own abstractions in order to refine mental models and explore data. Interactive maps enable this feedback loop.

42.2.1 Geo-visualization and GIS

A high degree of user interactivity opens a new world of opportunities and map use options. One of the most important is the ability to use the map as a tool for exploration and analysis, and not simply as a tool for presentation (Dykes 1997; Andrienko and Andrienko 1999; Edsall 2001; Crampton 2002). Over the past two decades, as GISs have evolved, theories within geographic visualization (or geo-visualization) have been developed to support the creation and use of maps and other associated representations for interactive analysis of complex spatial data sets. This approach in geographic information science generally involves a small group of expert users (often only one) that examines a phenomenon or set of phenomena through dynamic maps on a computer (MacEachren and Kraak 1997). Geo-visualization is characterized by highly interactive representations designed for use by individuals, expert in the understanding of the mapped phenomenon, to reveal previously undetected features of a data set. Recent research has indicated that, with innovative interaction techniques, geo-visualization can be facilitated even in collaborative situations, where multiple users, sometimes in different locations, can construct shared understanding of spatial phenomena (Rauschert et al. 2002; MacEachren 2005). Geo-visualization itself is not a set of tools and representations but is a process where human and computer interact continually to transform, select, and map data to a visual form in the quest for patterns and relationships (MacEachren, Wachowicz et al. 1999; MacEachren et al. 2004). With this new kind of map use, cartographers have become not only producers of well-designed maps for the communication of concepts, but also providers of opportunities (through user interfaces, modeling algorithms and visualization environments) for the exploration of data.

The connections between this shift in map use and GIS are clear. Geographic information systems, perhaps to a fault from a cartographic design point of view, were not developed for the presentation of information in the form of map output, but rather for the interactive analysis of spatially referenced information. A vast majority of maps created in GIS are ephemeral, existing for only the amount of time they are useful for an analyst. As such, they are meant to be seen by a single researcher or research group during the exploration of a geographic problem.

Exploratory geo-visualization often happens with a GIS at the center, but it can also occur with special-purpose software specifically designed to, for example, handle very large data sets through aggregation and/or other generalization forms (Fredrikson et al. 1999), represent many attribute variables at once through novel representation techniques (DiBiase et al. 1994; Erbacher et al. 1995; Dai and Hardisty 2002; Edsall 2003; MacEachren et al. 2003), simulate three-dimensional space with virtual reality motion and depth cues (Forsberg et al. 2006; MacEachren, Edsall et al. 1999; Fisher and Unwin 2002), or view the temporal nature of geographic data through map animations (DiBiase et al. 1992; Dykes 1997; Peterson 1999; Harrower 2004; Blok 2006). These applications, central to visual geographic analysis, are relatively difficult with “off-the-shelf” commercial GIS packages.

Often, the very personal activity of data exploration using maps involves the examination of those variables for features that might only be interesting to a single analyst with highly individualized mental models of the problem at hand. The uniqueness and specificity of data exploration tasks makes the creation of guidelines for representing and interacting with large disparate data sets with multiple variables relatively elusive (Haug et al. 2001). One way to begin a discussion about a framework for designing interaction with maps for exploratory visualization is to define a set of abstract roles of interaction to support data exploration.

42.2.2 The Roles of Interaction in Visual Analytics and Information Exploration

“Interaction is the fuel for analytical discourse.” (Thomas and Cook 2005, p. 9). Visual representations put the extraordinary power of the human mind to work in concert with sophisticated computational tools. Recently, the field of *visual analytics* has focused attention on the tremendous power of combining the cognitive resources of both scientists and domain experts with the interactive high-performance resources of interactive visual computing (Thomas and Cook 2005). At this point, work in this field has been primarily oriented toward developing research agendas and building bridges across disciplines that have previously worked separately on visual analytical theory and methodology. One of the major focus areas of visual analytics is “visual representation and interaction techniques,” and, while stressing the vital role of interaction in exploring information, the primary agenda document acknowledges that theories of how user interaction enables analytical thinking are few. It calls for the development of “a new science of interactions that supports the analytical reasoning process. This interaction science must provide a taxonomy of interaction techniques ranging from the low-level interactions to more complex interaction techniques and must address the challenge to scale across different types of display environments and tasks” (Thomas and Cook 2005, p. 9).

We believe that interaction techniques designed for data exploration have several basic roles, regardless of whether the data being represented are spatial. In upcoming sections, we describe specific modes of interaction that perform these roles.

First, interaction allows the environment to *compensate for the indispensable deficiencies* arising from representing information on a computer display. The depiction of data on a two-dimensional screen with limited resolution and size restricts the amount and form of visible information. In addition, regardless of the limitations of the screen, representing data also involves necessary biases associated with generalization and symbolization choices. Interacting with a computer environment (specifically, in ways detailed in Section 42.4.1), allows a user to access additional information and to use several different representation forms for multiple perspectives.

Second, interaction helps to *discover unobvious patterns* in data. Some patterns and relationships are only visible after much trial-and-error of manipulating the representation. Such manipulations might include rotations of scatter plots, transformations of axes or reordering

of a set of images. We describe interaction modes best-utilized for this role in Section 42.4.2. Using interactive capabilities for this purpose is useful and relevant for data sets of any size.

However, interaction is imperative, not simply relevant, to *explore particularly large databases*, defined both in terms of the number of data records and in terms of the number of attributes. Even millions of pixels may be insufficient to represent terabytes of information. In addition, the perceptual and cognitive capabilities of a human impose their serious limitations on the amount and density of the information a display may contain irrespective of its size and resolution. Only with interaction can all the data become accessible to an analyst. There are a number of interaction modes that are specifically designed to handle very large databases, which we categorize (in detail in Section 42.4.3) into two major types: *roll-up/drill-down* and *slice-and-dice*, which refer, respectively, to varying the levels of abstraction of data to give an overall impression, and the division of data into manageable portions. With the increasing prevalence of such data sets in geographic information science (GIScience), these modes will become more and more important in the design of interactive information systems.

We argue below that there are aspects of geographic inquiry that make visualization of *spatial* data distinctive. However, we also can borrow from (and support) research in related disciplines that are not particularly concerned with spatial data for some guidance in developing interaction for data exploration and knowledge discovery.

42.3 Designing Interaction for Exploration and Knowledge Discovery: Lessons from Outside Geography

The GIScience community can look outside its traditions for novel methodologies in interactive and/or visual analysis of large databases. These techniques are research priorities in the communities of statisticians, computer scientists, psychologists and graphic designers involved in exploratory data analysis (EDA), information visualization (InfoVis), and knowledge discovery in databases (KDD).

42.3.1 Exploratory Data Analysis

Statistics over the last three decades has witnessed the development of techniques that counterbalance a long-term bias in statistical research towards developing mathematical methods for hypothesis testing. Tukey (1977) saw exploratory data analysis as a return to the original goals of statistics—detecting and describing patterns, trends and relationships in data (both spatial and non-spatial). In this philosophy, EDA is about hypothesis generation rather than hypothesis testing. Though it need not be strictly visual, EDA is strongly associated with the use of graphical representations of data:

Most EDA techniques are graphical in nature with a few quantitative techniques. The reason for the heavy reliance on graphics is that by its very nature the main role of EDA is to open-mindedly explore, and graphics gives the analysts unparalleled power to do so, enticing the data to reveal its structural secrets, and being always ready to gain some new, often unsuspected, insight into the data. In combination with the natural pattern-recognition capabilities that we all possess, graphics provides, of course, unparalleled power to carry this out.

(NIST/SEMATECH 2006, Section 1.1.1)

Visual representations developed in EDA are often designed to complement confirmatory techniques, depicting data sets that can be gigantic, complex, multivariate, temporal, and/or spatial. The development of graphics for EDA has occurred somewhat atheoretically (with the possible exception of work by Wilkinson (1999)), with a large number of (very creative and

useful) tools and techniques developed for specific applications or problems (Keim and Kriegel 1994; Rao and Card 1995; Hummel 1996; Spence and Tweedy 1998; and many others). Recognizing the importance of spatially referenced information, statisticians have bolstered their visualization systems with mapping techniques borrowed from cartography and GIScience (Cook et al. 1997; Swayne et al. 1997; Unwin and Hofmann 1998; Carr et al. 2002).

The standard EDA “toolbox” contains representations designed for non-spatial data such as histograms, scatterplots and boxplots (Becker et al. 1988; MacDougall 1992). Adding dynamic features to these EDA tools have made them useful for data exploration. These dynamic features include both animation and interaction. Much of the work in EDA deals with developing ways of exploring complex numerical data. Many analogous techniques and innovative interaction modes have been developed for the exploration of abstract and/or non-numerical data. Such exploration falls into the related realm of *information visualization*.

42.3.2 Information Visualization

Information visualization (InfoVis) is concerned with the mapping of abstract data (like library card catalogs, web pages, financial transactions and mathematical functions, for example), and the design of such mapping has taken more creativity and originality than analogous mapping of physical data, which may already exist in some spatial context (like the atmosphere near the ozone hole, the interior of a human body, or the inter-molecular structure of a protein). This is a challenge that has led to novel and important research into using and interacting with the space of a graphic presentation to display complex information efficiently and clearly (Card et al. 1999).

The process of creating an information visualization representation from raw data, according to Card et al. (1999), is a “pipeline” of transformations and mappings, each stage of which, in a well-designed information visualization environment, benefits from human interaction. The general stages in the pipeline are *data transformations*, *visual mapping* and *view transformations*.

In the data transformation stage, raw data are translated into information that can be used in visualization by first deriving structure or value from them. This translation is accomplished by creating interactive tables of information (GIS practitioners would consider these highly interactive “attribute tables”) that can then be sorted, summarized statistically, classified, aggregated, or otherwise manipulated to give the information additional meaning to the researcher.

Visual mapping requires the abstraction and mapping of information not just to space, but also to color, position, size, visual hierarchy (connections between visual elements, like “branches” of a “tree”) and value. These visual variables are those that were described and implemented by Bertin (1983), and have, of course, been the subject of a large proportion of literature in statistical graphics and cartography. Skupin and Fabrikant (2003) argue that GIScience can contribute theoretical depth to this step, calling the visual mapping of abstract data “spatialization.” Tweedie et al. (1996) and Wise et al. (1995) are among several authors who emphasize user interaction in this step, enabling different sorts of visual representations to be created on the fly to conform to user needs.

Finally, “view transformations” refer to various abilities to alter parameters of the view itself, as opposed to the methods for mapping the data onto the view. Such transformations, according to Card et al. (1999) include adjusting viewpoint, altering distortion, and revealing additional information with an interaction such as a mouse-over, in which information is revealed when the mouse cursor hovers over specific text or graphics. View transformations also occur as a result of so-called *direct manipulation* interaction (Shneiderman 1997; North and Shneiderman 1999), through which the user may use the representation itself, and not buttons, menu items or other elements external to the display window, to alter what is represented. We shall argue that direct manipulation interfaces are particularly important in

spatial data exploration; interacting with the space of the representation itself allows users to think spatially when exploring spatial data.

In the next section, we demonstrate how interaction modes developed in EDA and InfoVis can be applied to spatial data analysis, and how these modes correspond to and complement existing methods for interacting with spatial data in GISs and interactive cartographic environments.

42.3.3 Knowledge Discovery in Databases

Though many EDA techniques, particularly those adapted by Tukey (1977), are visual, visualization is just one way of exploring statistical information. Visualization, for example, is one important component of analyzing very large databases. However, it is typically used in conjunction with other non-visual computational techniques that have been developed under the research umbrella of “knowledge discovery in databases” (KDD), of which the better-known procedure of “data mining” is a part (KDD consists of several generic steps: data preparation, data mining, interpretation of the results and reporting; see Miller and Han (2001)). The application of such computational data mining techniques with subsequent visualization of their results allows a human analyst to gain additional knowledge that cannot be (easily) gained directly from the viewing and manipulation of the original data. In modern KDD software, data mining results are represented in interactive displays. The interactivity is essential since the outcomes of data mining are often very voluminous and/or have a complex structure, which does not permit putting all information in a single static picture.

Some work has been recently done on designing interactive data mining techniques, where the user can guide the discovery process. However, as it is admitted in the KDD literature, guided knowledge discovery through interactive data mining is still in its infancy (Ceglar et al. 2003), perhaps because the visualization and graphical interfaces do not belong to the primary competences (and interests) of the mathematicians and statisticians designing and elaborating data mining methods. A closer cooperation with researchers in visualization, in particular, geo-visualization, would be of clear benefit for both sides.

Thus, a very effective and powerful exploratory environment for large spatial databases may be built by combining data mining with interactive maps (MachEachren et al. 1999; Andrienko et al. 2001a; Guo 2003; Koua and Kraak 2005). In such an environment, the analyst can first explore the data visually using interactive map displays. From this interaction, an analyst can gain the general idea of the data and uncover significant features that require a closer look. This directs the further investigation, including the choice of appropriate computational methods. Then, to interpret and make use of the results, the analyst will again need map displays which adequately represent the spatial aspect of the data.

Besides the obvious idea that KDD can aptly complement interactive maps in exploration of spatial data, it may be useful for designers of interactive mapping environments to adopt the view of data exploration and knowledge discovery as an essentially iterative process rather than a direct course from data to knowledge. An analyst often needs to return to one of the previous steps (data selection, data pre-processing, formulation of the question to be answered, selection of a data mining method, or setting method parameters) either for refining the results obtained or for testing their sensitivity to the selections and settings made in order to avoid possible biases and artifacts. This view is also relevant to the exploration of spatial data with the use of maps, which basically involves the same steps as KDD except that maps are used instead of data mining methods. In this process, the standard cartographers’ attitude to a map as a final product is no more appropriate. A designer of a mapping environment intended for exploration of spatial data should care about supporting all the steps of the exploration process, and enabling the iterative feedback loop. According to the steps involved, a minimum set of required interactive operations might include data selection (in particular, attributes, but also samples of data records), various data transformations (e.g.

from absolute values to relative or per unit values), selection of mapping techniques, and variation of their parameters.

In upcoming sections, we review specific methods from EDA, InfoVis and KDD that have proven (or would be) useful in representing and interacting with spatial and spatiotemporal data, and discuss in what ways the present capabilities of GIS complement those methods.

42.4 Exploring Spatial Information with Interactive Graphics: Justifications and Existing Techniques in GIS

In this section, we examine interaction forms present in existing GISs and classify them according to the roles for interacting with geographic information described in Section 42.2. Instrumental to the development (and wide usability and acceptance) of GIS—and indeed most software—was the introduction and adaptation of: 1) the spatial and user-friendly graphical user interfaces (GUIs) of operating systems; and 2) interaction devices—in particular, the mouse. The GUI was a non-trivial advancement of GIS because it took advantage of the well-established cartographic techniques of using the two dimensions of a map (in a GIS, the computer display) to represent two dimensions (x and y) of the surface of the Earth. Command line interaction, which might be useful and acceptable in the analysis of non-spatial data, removes a key cognitive connection between a user and spatial data: the map.

The map works uniquely as a visual representation of geographic data because it is *isomorphic* with the represented phenomenon (Arnheim 1997). The concept of isomorphism states that any representation on any level of abstraction needs to meet one condition: it must be structurally similar (isomorphic) to the pertinent features of the phenomenon being represented. Hence, effective exploration of the geographical space is impossible without an isomorphic representation of its pertinent features and relationships. From all existing types of display, only maps can satisfy this requirement.

Most of the interaction forms that make interactive maps effective for spatial data exploration take advantage of the isomorphism of maps on a computer display, and many other interaction modes (now present only in concept or in prototype systems) can be imagined that would increase the usefulness of interactive maps for exploration tasks.

Here, we follow the lead of EDA specialists Buja et al. (1996) and InfoVis pioneers Card et al. (1999) in organizing interaction modes according to task types. The roles we see for interaction with maps for exploring geographic information, as introduced in Section 42.2 above, include: 1) compensating for the indispensable deficiencies in the display; 2) revealing unobvious patterns in data; and 3) exploring large and complex databases.

42.4.1 Compensating for Indispensable Deficiencies in the Display

Because the cognition and understanding of maps on a computer display are limited by factors such as the display screen's resolution, color depth and two-dimensionality, as well as the visual perceptual limitations of the user, environments for spatial data exploration require interaction to compensate for these limitations. Present GIS and interactive cartographic environments feature methods by which these limitations can be (at least partially) overcome. Some of these are borrowed from (or replicated in) EDA and InfoVis environments. They include:

- *Zooming*. Presuming that there is sufficient detail in the raw (input) data, interactively adjusting the display scale restricts the extent of the view and can reveal features undetectable at smaller scales. This is, of course, common in interactive maps, and is used in more abstract representations such as scatter plots.

- *Panning, re-centering.* Upon restriction of the display extent such that data are hidden off-screen, capabilities become necessary to reveal the hidden information. In GIS, panning is enabled with click-drag actions, interface “arrow” buttons, or inset navigation maps, which show the display extent relative to the overall study area. Popular web-based interactive mapping systems have incorporated *animation* of these pan actions, representing a definite improvement over panning in discrete jumps with buttons or other navigation devices, and allowing for a more natural continuous scanning of our environment.
- *Re-projecting.* The two-dimensionality of computer displays (and static graphics such as paper maps) force a projection of multi-dimensional information. These “projections” include familiar map projections (at which GIS are adept) and also the projection of abstract data clouds (e.g. scatter plots of more than two variables; see Asimov 1985). Scatter plot matrices are multiple projections of data clouds, and are implemented and featured in many geo-visualization environments including those built with the GeoVISTA Studio toolkit (Gahegan et al. 2002) and particularly the work of Dai and Hardisty (2002) (Figure 42-3). In GIS, map projections can be altered through dialog boxes, pull-down menus, and form fill-in interaction, but using the mouse to *rotate* a three-dimensional scene also serves to re-project the representation. Rotation has long been identified as essential for the recognition of patterns and features in an abstract data representation, revealing features (such as in a three-dimensional data cloud) that would otherwise be obscured from view (Becker et al. 1988; Hurley and Buja 1990).

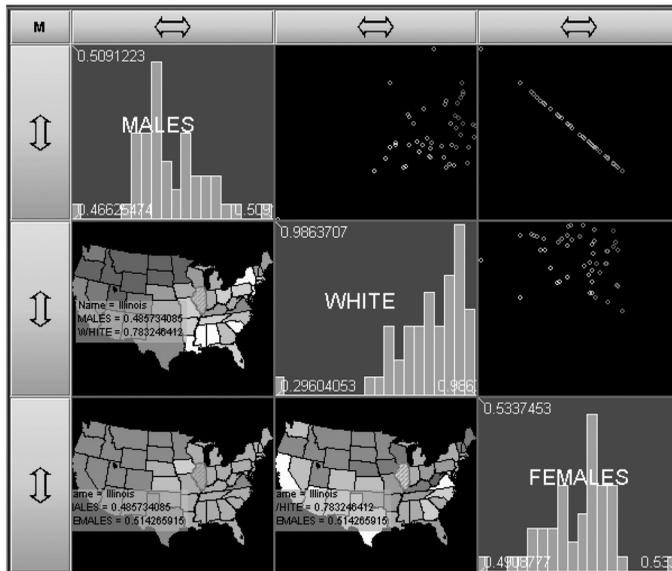


Figure 42-3 Conditioned manipulable scatter plot matrix of Dai and Hardisty (2002). The scatter plot matrix represents a form of projection of a multidimensional attribute data set; in this case, a three-dimensional data cloud is projected in three different ways (with corresponding choropleth maps). The matrix could contain two-dimensional projections of an indefinitely high number of dimensions. “Strumming” and “accessing exact values” are also illustrated: mouse-over actions immediately reveal details and are linked to corresponding glyphs in other windows. See included DVD for color version. Source: Dai and Hardisty (2002).

- *Accessing exact data.* Typically in maps and other graphics, data items are encoded by symbolic representations. However, the extraction of exact data from the graphical feature (particularly if it has been simplified, symbolized or classified) is difficult for a user. An interactive map can provide easy access to the exact data standing behind graphical features. This is a typical operation in a GIS, for example, as data can be shown in a special window when the user points to an element in a map.

- *Focusing* involves increasing the legibility and degree to which display elements may be differentiated (so-called *display expressiveness*) of a subset of data. Even high-definition displays are limited in legible sizes and differences in symbols. Through the selection and re-symbolization of a subset of data, focusing reveals detail within the subset and de-emphasizes the differences in the data set as a whole. Owing to the conceptual similarity to display zooming, which enlarges a selected part of a display area in order to improve its legibility, focusing may also be called “data zooming.” A specific case of focusing is removal of outliers, i.e. extremely high or extremely low values standing far apart from the bulk of the data, from the display.

42.4.2 Revealing Unobvious Patterns in Data

The revelation of previously unrecognized features or patterns in a data set is one of the basic purposes of cartography in general. However, comprehensive data exploration is best supported by interactive methods to alter the methods of abstraction, giving unique and potentially important perspectives on the information. Some of the ways these multiple perspectives can be created in present GISs include:

- *Altering representation type.* Though cartography has long-standing guidelines regarding the appropriateness of symbolization schemes for different types of data, symbolization for data exploration must be flexible enough to support non-traditional strategies in order to reveal patterns. Switching between a choropleth and proportional symbol map, for example, may prompt different mental models of the information and facilitate insight.
- *Altering symbolization.* Within a chosen representation type, data exploration can be supported by simple interactions that allow the alteration of symbolization choices such as classification schemes, color schemes, interpolation type, and contour intervals. Figure 42-4 shows an example of this in the CommonGIS environment of Andrienko et al. (2001b). Again, traditional cartographic guidelines governing such choices for data communication to wide audiences may not be ideal for private data exploration.

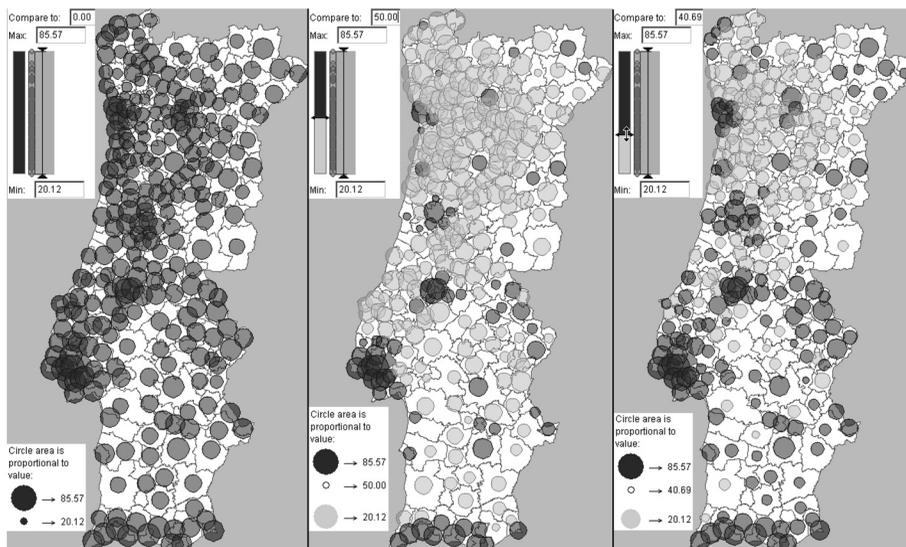


Figure 42-4 Altering symbolization (here, in the CommonGIS environment of Andrienko et al. (2001b)) facilitates revealing unobvious patterns in data. Left: the percentages of working people employed in services are represented by graduated circles whose sizes are proportional to the values they represent. Center: the symbolization has been changed so that two colors are used to represent the values below and above an interactively specified reference value, 50%. Salient spatial patterns are immediately noticeable. Right: the reference value can be dynamically changed, e.g., by moving a slider (top left of the map). In response, the map is automatically redrawn and can expose new interesting patterns.

- *Posing queries.* Maintaining the isomorphism of maps is also reflected in the spatial nature of many queries in GIS, particularly the ability to make selections with a tool that draws a box (or, more generally, a “lasso”) directly on the map. Selecting (by drawing a box or lasso, or by pointing and clicking) points, lines or polygons according to their spatial arrangement, rather than a value of a thematic variable, gives privilege to the spatial nature of GIS queries.
- *Transforming data.* Manipulation of the data represented in a map often allows an analyst to see what was previously not evident. One of the most commonly used transformations is the derivation of relative data from absolute data, for example, proportions of parts in a whole, densities or amounts per capita. Statistical standardization is often applied when several attributes need to be jointly explored and compared. Computing of changes is used when data refer to several time moments (Figure 42-5). Interpolation and smoothing are applied to data representing spatially continuous phenomena, which are typically specified in raster (grid) form.

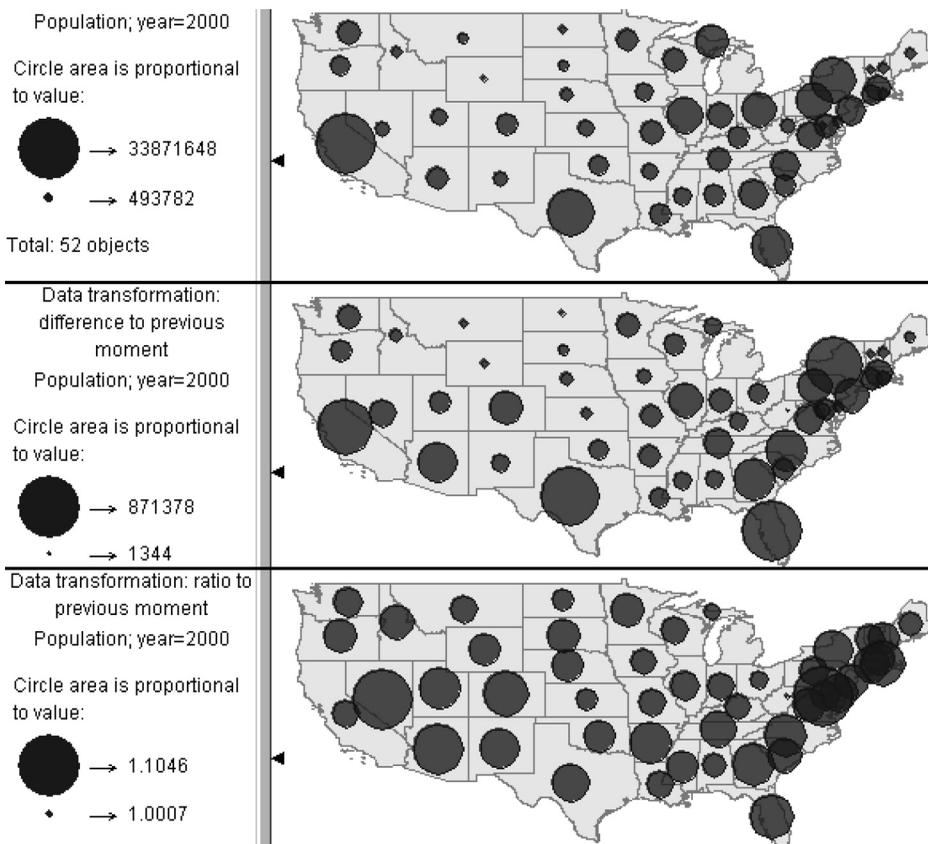


Figure 42-5 Three screenshots of the same map demonstrate an interactive application of data transformation (also from the CommonGIS environment of Andrienko et al. (2001b)). Top: the circles represent the absolute population numbers in 2000. Middle: the absolute population numbers in 2000 have been transformed to differences in comparison to 1999; the circles now represent the differences. Bottom: the circles represent the relative changes (ratios) with respect to 1999. Note the explanations in the legend on the left of the map.

42.4.3 Exploration of Voluminous and/or Multidimensional Databases

Spatial data can be particularly voluminous, and also can have dozens or hundreds of thematic variables associated with each record. Interaction is imperative for the exploration of such databases, assisting in several related but separate conceptual operations. *Roll-up* is a means of simplifying by means of aggregation, generalization and abstraction. By means of this “rolling up,” the analyst can get an overview of the entire data set and build a simplified mental model of it. Verification of this model is accomplished by *drill-down*, an approach by which an analyst can view portions of the data closer to its raw (not abstracted) form. These two operations are often used in concert with one another. Another approach facilitated by interaction is *slice-and-dice*, which divides the data into manageable portions and allows separate exploration of these portions. The partial mental models obtained in this way must then be united in an overall model of the entire data set. Figure 42-6 illustrates the concepts of rolling up, drilling down, and slicing and dicing in CommonGIS.

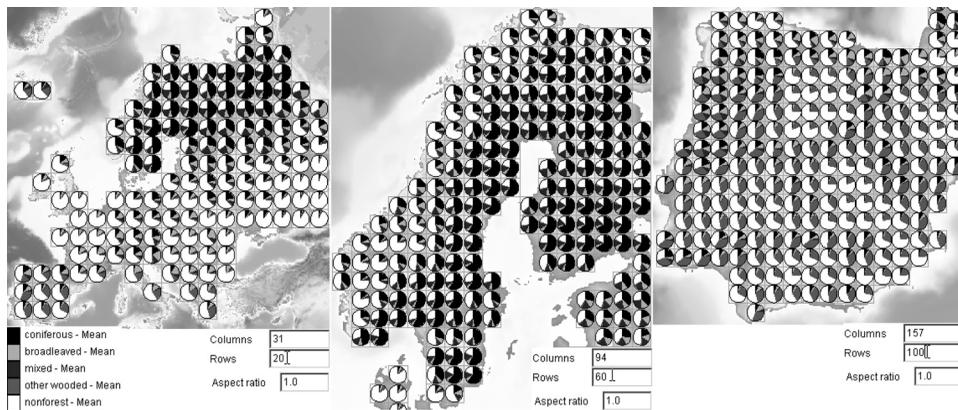


Figure 42-6 An illustration of the concepts of roll-up, drill-down and slice-and-dice. The original data about the proportions of different types of forests and non-forest land are specified as 5 high-resolution rasters, where each raster contains 40 million values. In order to get an overview of the distribution of forests over Europe, the data have been aggregated by cells of a coarse grid (roll-up). The aggregated values (specifically, the mean values in the cells) have been represented using pie charts. The analyst can select parts of the territory (slice-and-dice) and decrease the level of aggregation for these parts (drill-down) in order to examine the data in more detail. Irrespectively of the chosen level of aggregation, the interactive map preserves the representation type and symbolization parameters, which are re-applied to the data after each re-aggregation operation.

Interaction can support roll-up and drill-down in natural and convenient ways. For example, a GIS or other interactive map can be set to intelligently zoom, increase and decrease the level of detail when the user changes scale. Interaction can support slice-and-dice by enabling an analyst to divide a data set into portions and consider, for example, the south of a country separately from the north or urban areas separately from countryside. More subtly, interaction also is important in the synthetic activity of building an overall model from partial ones, which requires intensive comparisons between portions to extract similarities, note differences and establish relationships.

There are other interaction forms of present GIS and cartographic exploration systems that seem particularly well suited to the role of handling large complex databases. Among these are:

- *Toggle visibility* of loaded themes. Though a fundamental operation in GIS, the ability to select themes on a map is an extraordinarily powerful interaction mode, allowing for comparison of a subset of dimensions from a large multidimensional data set. This partially replaces the necessary bias of non-interactive maps created by the cartographer’s selection of particular themes.

- *Brushing and linking.* In most GISs, a subset of records of a large data set is selectable through a spatial query (e.g., the lasso tool on a map, described above) or through an attribute query (selecting records that are similar along one attribute dimension after sorting an attribute table). This brushing operation is often used in combination with linking, through which selected records in one view (e.g. the map) are also selected (and manipulated) in other representations (e.g. tables, charts, other maps). A recent effective application of these techniques is the Exploratory Spatio-Temporal Analysis Toolkit (ESTAT) environment (Figure 42-7) of Robinson et al. (2005).

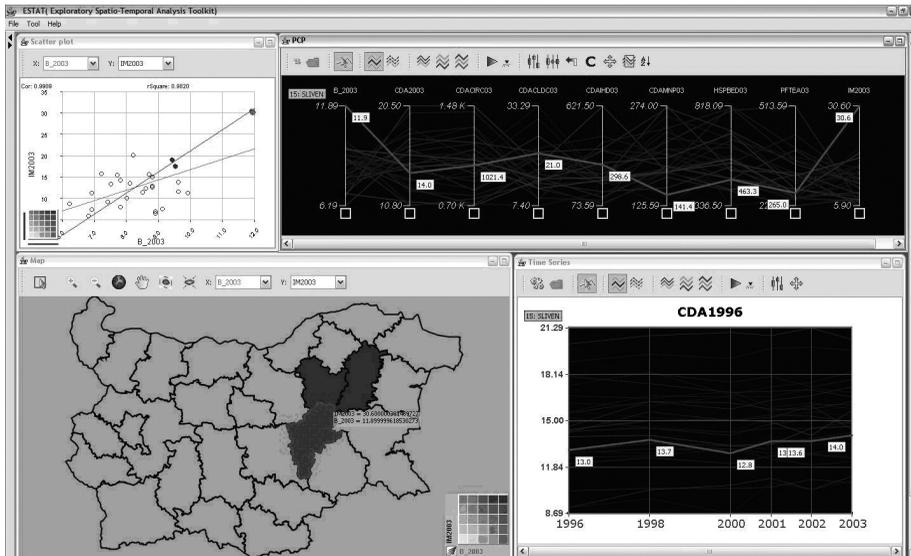


Figure 42-7 Exploration of spatial data through brushing (Robinson et al. 2005). A user selects a single enumeration unit (on map in lower left, or any of the windows) and all corresponding glyphs and traces are highlighted in other windows. Brushing can also occur with multiple spatial units to uncover regional patterns in attribute or temporal spaces, or with multiple attribute or temporal units to uncover corresponding patterns in the spatial representation. See included DVD for color version. Source: Robinson et al. (2005)

- *Conditioning.* Conditioning (or *filtering*) typically uses slider bars or other graphical interface tools to perform attribute queries on individual variables, displaying, for example, only those points between two values of one important variable (Carr et al. 2005). Conditioning reduces the amount of data displayed by displaying only those records that meet certain criteria (Figure 42-8).

42.5 Supporting Exploratory Spatiotemporal Visualization with GIS

In this section, we imagine an interface for geographic information that includes windows that each affords access to one (or more) of three aspects of geographic data: the spatial component, the temporal component and the attribute(s) component (following the TRIAD model of Peuquet and Qian 1996). Many interaction forms can be utilized in any of these interface windows of a GIS. Brushing, for example, can be implemented in the spatial representation (the map display), the attribute representation (the database table, or a graphic version of the attributes such as a scatter plot or parallel coordinate plot), or the temporal representation (if one would come to exist as standard in GIS—presently, timelines and other temporal query and display widgets are not standard). We organize the following ideas for interaction with spatiotemporal information through a GIS according to these three

dimensions (space, time and attribute); however, many of these concepts below can be implemented in parallel ways to other displays.

42.5.1 Extending the Forms of Interaction with Spatial and Attribute Dimensions in GIS

Present GISs are designed to facilitate the analysis of the spatial and attribute dimensions of geographic data, and the discovery of connections between these two dimensions. A typical GIS query, for example, often requires an attribute “sort” (display only those units in a certain range of some variable) and a spatial “sort” (display only those units a certain distance from a selected polygon). We believe that this emphasis can inspire new interaction methods that would facilitate the exploration of these two dimensions of geographic data. Below is a non-exhaustive but hopefully provocative survey of interaction forms that might assist in the understanding of large, multivariate, disparate and/or complex geographic information.

- *Strumming*. Many of the representations that GIS might borrow from the EDA toolbox consist of relatively confusing and complicated displays. A scatter plot matrix, for example, is enhanced when a mouse-over of one point leads to the highlighting of all corresponding points in the matrix (Cleveland 1985, pp. 210–218). Dai and Hardisty (2002), among others, have adapted a type of mouse-over capability to maps and other corresponding statistical displays (see Figure 42-3). By simply passing a cursor over an object (e.g., an enumeration unit on a map, a point on a scatter plot, or a row of a table) or pixel (e.g., in a raster image), a user may highlight that unit of the display. Parallel coordinate plots (Inselberg 1985; Inselberg 1998; Edsall 2003) are vastly improved when the entire trace (representing the multivariate signature of one record) is highlighted upon the “strumming”—like a guitar string—of one segment of the trace. This /strumming capability alone is not particularly useful, but when corresponding symbols, either in the same display or in other representations, are highlighted automatically with the strumming, complex displays can be simplified and the construction of knowledge is facilitated. Conceptually similar to linking (discussed as a present capability of GIS above), strumming, unlike linking, also can be utilized within a single, complex data display, and works with a simple mouse-over, reducing the need for fine-scale dexterity with the mouse.
- *Lensing*. Adopting a popular mode of interaction from InfoVis, GIS could use lensing, which simulates a fish-eye lens or other physical magnifying tools to highlight a region while deemphasizing unlensed regions (Leung and Apperley 1993; Stone et al. 1994). This adds detail to a region of interest, distorting its surroundings and reducing their visual importance but allowing them to remain visible. This is conceptually similar to zooming, which necessarily hides parts of the map or display that are not within the restricted extent of the view, but allows for (highly generalized) visualization of the parts of the data set that are not the focus of attention.
- *Manipulating symbolization with data-rich interactive tools*. Exploratory tasks are facilitated when a user is able to visualize as much information as possible. Classification and other methods of symbolization are more informative if they are associated with representations of distributions (even in the legend itself), such as histograms, parallel coordinate plots or scatter plots. In the context of map animations, Peterson (1999) called these “active legends.” Recent prototype environments (Andrienko and Andrienko 1999; Andrienko et al. 2001b; Edsall 2003; Haug et al. 1997) allow for dynamic reclassification and color scheme manipulation by interacting directly with such representations via movable elements like slider bars, rather than via text fill-in boxes or command-line interactions. Interactive classification and representation changes are core components of the GeoVISTA Studio toolkit (Gahegan et al. 2002; see Figure 42-7).

Adding interactivity to the legend allows for on-the-fly adjustments to the classification scheme to better align the symbolization to the mental model of the user than the default schemes in GIS (equal interval, quantile, natural breaks, etc.).

42.5.2 Extending the Forms of Interaction with Temporal Information in GIS

The representation of, and interaction with, temporal aspects of geographic data, both in GIS databases and GIS displays, have been the focus of researchers who acknowledge the need for analysis and representation of process rather than stasis in geographic inquiry (Langran 1992; Peuquet 1996; Wachowicz 2002; Andrienko and Andrienko 2006). In its representations and graphical user interface, GIS presently gives privilege to the spatial and attribute relationships among data. Advances must be made in the database representation of spatiotemporal data; such advances will lead to and require innovations in the visual display (and its associated interactive capabilities) of the temporal geographic data. If, as Frank (1993) succinctly states, “the interface is the system” to users of GIS, simply adding interface tools that enable interaction with the temporal dimension of geographic information might make investigation of time in geography more central and fundamental to users of GIS. Some of the ways that users might be able to interact with temporal geographic data include:

- *Constructing and controlling animation.* Animations are the temporal analogy of maps—while maps represent physical space as display space, animations represent physical time as display time (DiBiase et al. 1992). As such, animations are isomorphic to their represented phenomenon, and logically should be the first choice to represent temporal information. GIS interfaces that might support animation should borrow concepts from animation software in order to make animation construction and viewing intuitive. Exploratory tasks with temporal data might be facilitated by reordering the frames according to a variable other than time, similar to “mapping” geographic data onto an attribute-based representation such as a histogram.
- *Temporal panning.* Buttons that mimic VCR controls, including start, stop, pause, fast forward, and rewind, are logical to include on any moving representation in order to reduce the cognitive disadvantages of animation (including “disappearance,” in that users are asked to remember the state of a phenomenon from several frames before in order to compare it to the current frame; see Harrower (2003) for a survey of animation design choices). Some animated maps include a useful “rock” function that allows a user to move back and forth from one frame to the next and back again, over and over, in order to detect changes between a pair of moments in time. Temporal panning is applicable not only to animated maps but also to maps representing temporal variation by means of diagrams or symbols (Figure 42-9).
- *Temporal zooming.* More difficult to implement but likely necessary for creative exploration would be a temporal zoom tool. These tools could take several forms. First, to preserve the time-to-time isomorphism, a “zoom-in” on the timeline tool would increase the temporal scale. We define such a scale in the same sense as a map—1:86,400 would imply that one second of animation time would be equivalent to 86,400 seconds (one day) of real world time. A temporal zoom might increase this scale such that one second of animation would be equivalent, say, to 21,600 seconds, or six hours. If the data supported it, this zoom would, in effect, slow down the animation to highlight a segment of the animation of particular interest. The inverse also could occur, of course—a “zoom out” would devote fewer frames per unit real time (this opens new questions, not in the scope of this chapter, about methods of temporal generalization and extrapolation).

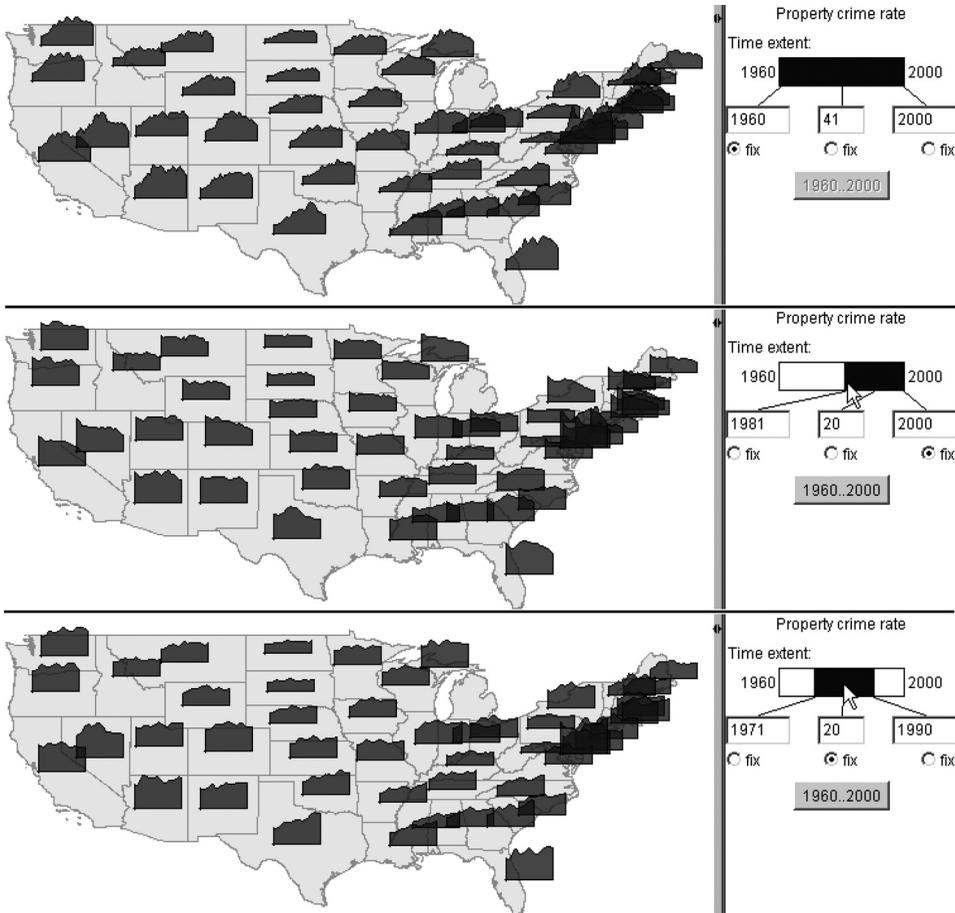


Figure 42-9 Top: the symbols on the map show the dynamics of the property crime rates in the states of the USA over the period of 41 years from 1960 to 2000. Middle: the user has interactively reduced the represented time interval to 20 years from 1981 to 2000. Bottom: the user shifts the 20-year interval along the time axis, which results in the map being dynamically redrawn.

- Temporal querying.* Standard “timelines” form the most typical representation for time passing on an animation. However, this interface metaphor (time “moving” from left to right) may limit the creative exploration of information, particularly those temporal data that are periodic or cyclic in nature (Edsall and Sidney 2005). Ideal exploratory interaction techniques would allow for the selection and/or ordering of frames of an animation differently from simple linear time. This linear-cyclic distinction might be manifested in a GUI through a temporal querying tool, a graphical representation of time that can alternate between a “time line” and a “time wheel” at the user’s request (Edsall and Peuquet 1997; Edsall 2001). In the case of the wheel interface tool, the user might specify the period of the cycle represented and choose to query only those dates that correspond to a specified duration within the cycle. For example, suppose a researcher were interested in the variation of rainfall each monsoon season over several years. He or she would customize the time wheel to a yearly period and then select the days, weeks, or months of interest to limit the investigation.
- Temporal data transformation:* A map can be supplied with interactive controls allowing the user to apply various data transformations, for example, from the original values to the changes (differences or ratios) with respect to the previous moment or a selected moment (Oberholzer and Hurni 2000; Andrienko et al. 2001c). The map immedi-

ately would react to the actions of the user by re-applying the current representation technique and symbolization parameters to the transformed data. Besides computing changes, useful transformations for time-dependent numeric data might include temporal smoothing, which hides minor fluctuations and exposes major trends, and comparison to the running mean or median for the whole territory or to the local mean or median in each place. A possible user interface for interactive transformations of time-dependent data is demonstrated in Figure 42-10.

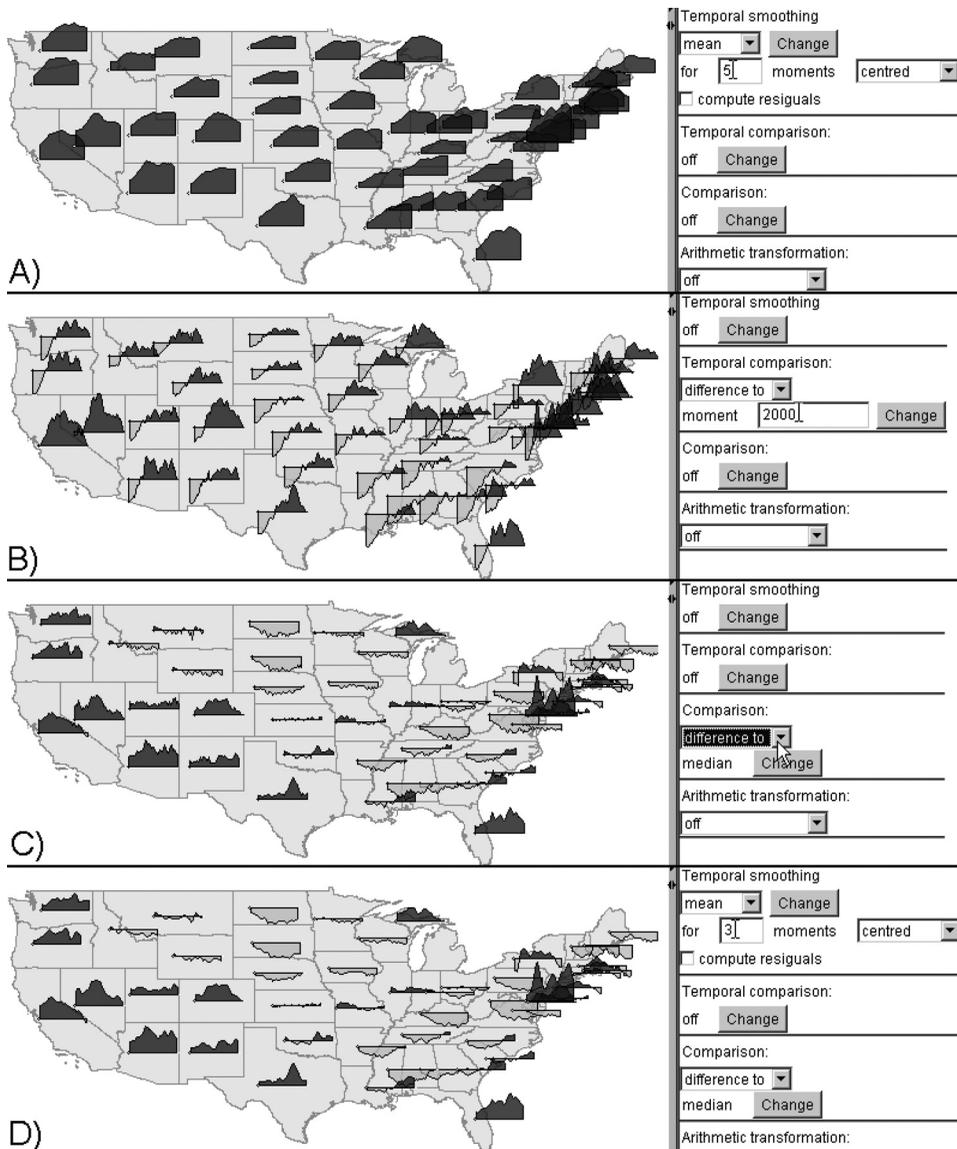


Figure 42-10 Various transformations can be interactively applied to time-series data represented on a map in CommonGIS. A) Temporal smoothing (compare to the map in Fig.9 top). B) Comparison to a selected time moment. C) Comparison to the country's running median, i.e., the values in each year are compared to the country's median in this year. D) It is possible to combine two or more transformations, for example, smoothing with comparison to the running median. In maps B, C, and D, the darker shade corresponds to positive differences and the lighter shade to negative differences.

42.6 Summary

In this chapter, we have described and examined a multitude of different modes of interactivity that either exist presently in modern GIS or might benefit GIS if they were widely implemented. The focus here has been on the interaction with maps and graphics with the goal of exploring spatial (and spatiotemporal) data; this contrasts somewhat with typical roles of GIS which include confirmatory analysis and data communication. While user interfaces of present GISs would almost never be described as “intuitive,” they do provide a remarkable range of interaction possibilities that position GIS well as an environment for exploratory tasks. With some additional techniques and theories of interaction borrowed from other disciplines, particularly human-computer interaction, information visualization and knowledge discovery in databases, GIS could evolve into a more natural exploratory tool. In doing so, it would support tasks such as compensating for limitations in the display, discovering unobvious patterns in data and examining particularly large spatial databases about which little is known going into the analysis.

We have chosen in this chapter to limit our survey to those techniques and systems designed for interaction of a single human analyst with a single desktop computer. It is unrealistic, however, to assume that data exploration and expert-driven analysis will occur solely in this mode. Particularly in the realm of visual analytics, the combined efforts of many analysts working collaboratively often lead to the greatest insight (MacEachren 2005). Mouse-based interaction will not be sufficient for exploratory analysis in group work, and interfaces need to be multi-modal, responding to not only mouse actions but also, possibly, gestures and voice commands (Rauschert et al. 2002). Additionally, theoretical and empirical examinations of the influence on the globalization of visualization may be necessary to maximize the capabilities of interactive maps for spatial data exploration; with the internet, the ability to carry out international collaboration with users of diverse cultural backgrounds will prove to be powerful. However, it may be necessary to examine differences in symbolic conventions and social interaction customs in order to design representations and interactions to involve diverse users (Marcus 2001; Shen et al. 2006; Edsall 2007).

In this chapter, we hope to persuade users and designers of GIS to appreciate the great power of interactivity in present systems. Interaction through GUIs is isomorphic with—and therefore highly appropriate for—the spatial analysis priorities of GIS, enabling the space-based queries and visualization that today’s GIS users take for granted. GIS would benefit from expanding those capabilities in order to interact with other dimensions of GIS data, through, for example, spatialization of abstract and/or attribute data, or animation and/or transformation of temporal data. Research in related fields such as geo-visualization and information visualization can be utilized for designing such interaction. In this chapter, thus, we also hope to inspire users and designers to consider the potential of GIS for spatiotemporal data exploration through innovative representations and interactions that represent natural extensions of existing systems.

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