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An evolving cognitive-semiotic approach to geographic visualization and knowledge construction

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Abstract

In this short essay, I consider some relationships between the integrated cognitive-semiotic approach to cartographic representation that I develop in How Maps Work and Jacques Bertin's contributions to cartographic and graphic theory. I relate my approach to his comprehensive semiologic framework for map and graphic design as well as his efforts toward a structured method of graphic information processing. In relation to the former, particular attention is given to critiques of Bertin's "graphic variables" and work that extends them into the domains of time, sound, and touch. Then, the commonalities between his concept of geographic information processing and recent developments in geographic visualization (geovisualization) are outlined. Following from the latter, three geovisualization research challenges for the coming decade are highlighted: (1) developing a typology of operations for interactive georepresentations and a syntactics for their use; (2) balancing abstraction and realism in GeoVirtual environments; and (3) facilitating different place collaboration.

keywords: geographic visualization, dynamic cartography, interactivity, animation, semiotics, cognition, virtual environments

Introduction

I am honored to have an opportunity to contribute to this issue of the *Information Design Journal,* with its focus on the work of Jacques Bertin. His books *Semiology of Graphics* and *Graphics and Graphic Information Processing* have been stimuli for my own thinking about the representation and analysis of geographic information. I have also used both books as core readings for graduate seminars and they have generated lively discussion and prompted innovative research. I often ask graduate students to consider how cartographic research and practice in the U.S. might be different today if the English edition of *Semiology of Graphics* had appeared in 1967 (when it was published in French), rather than in 1983. I know that my own work would have been dramatically different if I had encountered these ideas a decade and a half sooner.

Semiology of Graphics (Bertin 1983), includes many insights (and contentions) that have provoked research by individuals in a variety of disciplines. Like many others, I have grappled with the strengths and weaknesses of Bertin's small set of "fundamental" graphic variables, and offered two variations on them (MacEachren 1994a, MacEachren 1995). A group of colleagues, students, and I have also proposed extensions into dynamic display environments (DiBiase et al. 1992, MacEachren 1994b, MacEachren 1995) and have developed a typology and syntactics for methods used to map quantitative data (MacEachren and DiBiase 1991). Beyond these direct affects on my work to formalize components of visual representation, *Semiology of Graphics* prompted me to explore semiotics (the North American term for semiology) in greater detail. Bertin's contentions concerning how users process maps and graphics visually were among the factors that led me to consider how a semiotic approach can and should be linked to our growing understanding of human visual perception and cognition. The result of this thinking is an integrated cognitive-semiotic theoretical perspective on cartographic representation that I present in the first two sections of *How Maps Work: Representation, Visualization and Design* (MacEachren 1995).

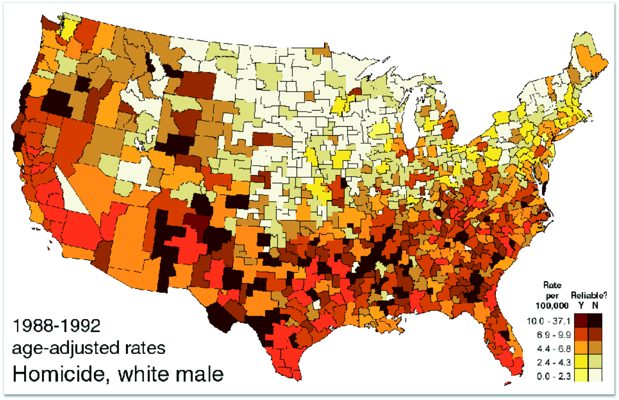
In *Graphics and Graphic Information Processing,* Bertin (1981) offers a view of maps and graphics that emphasizes their role as methods for processing and analyzing information – a view quite different from the prevailing communication paradigm in North America at the time. From roughly the mid-1950s through the mid-1980s, North American cartographic research focused on the role of maps as information storage and communication devices. I was uncomfortable with this paradigm well before reading Bertin, directing my attention first to cognitive aspects of map use that were not grounded in the communication paradigm (MacEachren 1986, MacEachren 1990). Soon after, I began to focus on the concept of geographic/cartographic visualization (geovisualization) as a method of map use that goes beyond simple information communication to enable knowledge construction about the geographic scale (i.e., neighborhood to global) natural and social environment (MacEachren 1994c, MacEachren and Ganter 1990, MacEachren and Kraak 1997). My approach to geovisualization has been influenced most directly by related efforts in Visualization in Scientific Computing (ViSC), exploratory data analysis (EDA), and information visualization. Bertin's *Graphics and Graphic Information Processing*, however, was also an early stimulus for my ideas. I believe that Bertin's perspective on graphic information processing complements current thinking in geovisualization and that it continues to have much to offer as a source of inspiration.

In the next two sections I expand on the above characterizations of Bertin's two most critical contributions to consider key research efforts in cartography and geovisualization that have been stimulated by or that complement Bertin's semiology and graphic information processing ideas.

Extending the concept of "graphic variables"

Perhaps the best known, and most often cited aspect of Bertin's work is his delineation of a set of fundamental graphic variables (location, size, value, texture/grain, color, orientation, and shape) and rules for their use. These variables have been analyzed, critiqued and extended by a series of authors (e.g., Spiess, 1970, Morrison 1974, MacEachren 1994a). Research directed to critique and assessment of Bertin's graphic variables and associated application rules has focused on four questions: (1) are the variables he delineates sufficient to account for all possible graphic variations, (2) are his contentions about the appropriate application of the graphic variables correct, (3) what are the implications of combinations of variables, and (4) how, if at all, does evolution in graphic display technology change the number or characteristics of graphic variables that are considered to be "fundamental."

In relation to the first question, attention has been directed primarily to aspects of color and texture (or pattern). For the latter, *arrangement* of elements has been proposed as a variable (MacEachren 1994a, Morrison 1974) and a distinction has been made between *density* of texture elements and their *size* (MacEachren 1995). Size of texture elements corresponds to Bertin's "grain," while density of elements (lines per inch) is unaccounted for in Bertin's system. For color, most cartographers (and those in other graphic fields) recognize three attributes (hue, saturation or chroma, and lightness or value). Bertin chose to omit saturation, perhaps because he thought it less important than the others (or because existing printing technology did not enable its precise control). Saturation, however, is easily controlled independently using current computer technology and is often used to create a distinction between foreground and background information (Brewer 1992). Several authors have also pointed to the logic of using saturation (sometimes called purity of color) as a device to represent data certainty, with highly saturated colors for certain data and unsaturated, grey, washed out colors for uncertain data (MacEachren 1992, McGranaghan 1993) – see color plate 1.



color plate 1. A map of white male mortality due to homicide for the health service areas of the U.S. The map depicts mortality using a sequential color scheme with dark (red-brown) representing high mortality and light (yellow) representing low mortality. Health service areas for which the mean value is a potentially unreliable reflection of the region are represented as being less reliable by use of desaturated colors. For experimental results comparing this method with others, see MacEachren, Brewer, and Pickle (1998)

In relation to the second question, a frequent criticism leveled is that Bertin provided no empirical evidence in support of his contentions, nor any grounding in perceptual and/or cognitive research. His explanation for this "omission" is provided in his own essay within this issue. Although not based on empirical research or cognitive theory, many of Bertin's contentions are intuitively appealing and have found their way into standard cartography texts (Kraak and Ormeling 1996, Robinson et al. 1995, Slocum 1998). Empirical research designed to assess several of the contentions has been carried out. While many of Bertin's contentions remain to be addressed (MacEachren 1995), a majority of the ones tested to date have been supported, at least in part. One example is work directed to exploring the contention that color value is an effective variable for representing ordered data while color hue is not. Early research supported this hypothesis (Cuff 1973, Gilmartin 1988). Other research, however, has demonstrated that hue-value combinations can be more effective than value alone (Speiss, 1970, Brewer et al. 1997).

In relation to the third question, map representation seldom relies upon a single graphic variable. Thus, it is important to understand the interaction among variables. Spiess (1970) showed that, in general, only those properties common to all variables are maintained or reinforced. Competing properties are weakened. Similarly, Dobson (1983) demonstrated the potential of "redundant" representational components for thematic maps (e.g., use of size and color value to signify the same information). Carefully selected combinations, then, can provide better selectivity than pure variables and also seem to support more accurate judgements at the interval level of measurement. This is particularly important for monochrome maps.

In relation to the fourth question, technology is providing new graphic variables, one of the more important of which is *transparency* (also called opacity). With current computer graphic technology, manipulating the transparency of any object (whether point, line, or area) is an operation comparable to that of controlling any of the graphic variables originally identified by Bertin. In similar ways it is now quite easy to manipulate the "*crispness*" (or "fuzziness") of object edges (MacEachren 1992, McGranaghan 1993, van der Wel, Hootsman, and Ormeling 1994). This, for example, can be an effective way to represent the uncertainty of classification on a land cover map (figure 1).

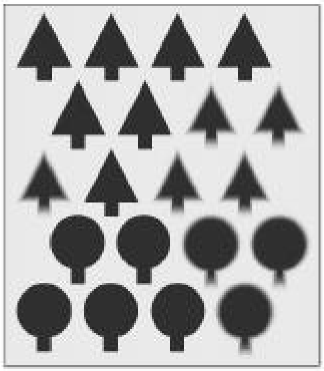


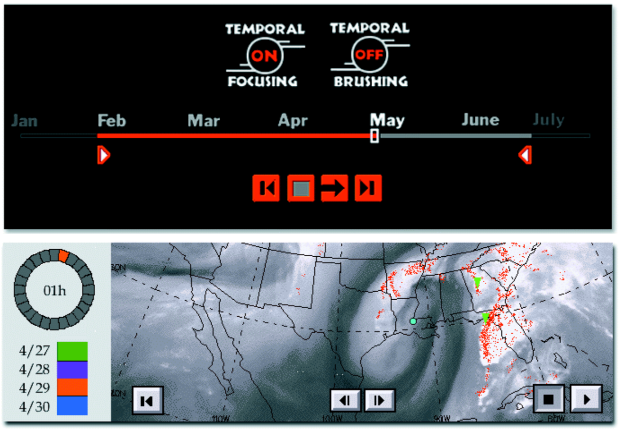
figure 1. A depiction of two forest types on a land cover map. Regions in which classification is uncertain are indicated by fuzzy symbols.

In addition to extending the representational possibilities of static maps and graphics, technology has made it easy to add touch, temporal variation, and sound to the realm of graphic/cartographic representation. Not surprisingly, researchers have proposed sets of tactile (Vasconcellos 1993), dynamic (DiBiase et al. 1992, MacEachren 1995), and sonic (Krygier 1994) variables – all modeled on Bertin's approach. Vasconcellos' tactile variables include volume (position in 3D space), size, value (density), texture/grain, form (shape), orientation, and elevation. These are nearly a direct match to Bertin's original graphic variables, with color hue (a variable suited to depicting qualitative differences) being replaced by elevation (a variable suited to ordinal depiction). Implementing the tactile variables has become practical using special heat sensitive "bubble paper" for use in laser printers. Developments in virtual environment technologies suggest that we should now consider a full range of kinesthetic "variables" that go beyond touch to include resistance, friction, kinesthetic location, and perhaps others (Griffin, 1999).

Both dynamic and sonic variables require observation of a display over time. Krygier's (1994) set of sonic variables includes several that are relatively direct analogs of graphic variables, but do not have a complement among the dynamic variables identified thus far: loudness ~ size, pitch & register ~ value, timbre ~ shape. Variables common to dynamic visual and sonic representation include several that deal directly with time, specifically duration, position (in time), order, and rate-of-change. Duration matches with the graphic variable of size while temporal position corresponds to Bertin's spatial location. Like texture/grain within the graphic variables (which requires multiple visual elements across an expanse of space), order requires multiple elements across an expanse of time. Rate-of-change also requires an expanse of time, but is usually considered to apply to a single dynamic or sonic object. Attack/decay (identified only as a sonic variable) should probably be considered as a variant of rate-of-change. Frequency and synchronization have, thus far, been proposed as dynamic but not as sonic variables. Here, I suggest, however, that both are as relevant to sonic representation as they are to dynamic visual representation. They both (like order) require multiple (at least two) entities interacting over time. Frequency relates to multiple entities in a spatially integrated display while synchronization deals with spatially separated components (e.g., paired maps in adjacent windows or sounds from opposite sides of a headset).

Graphic information processing ==> geovisualization

Geovisualization, from my perspective, is about the use of visual geospatial displays to explore data and through that exploration to generate hypotheses, develop problem solutions, and construct knowledge (MacEachren and Ganter 1990, MacEachren 1994c, MacEachren 1995, MacEachren et al. 1999). Along with this fundamental goal of visualization, one of the key factors that initially distinguished geovisualization from traditional cartography was an emphasis on highly interactive displays. While interactivity is beginning to permeate all aspects of cartography, it remains at the core of research directed to geovisualization (Kraak 1994, Kraak 1998, Kraak, Edsall, and MacEachren 1997, MacEachren and Kraak 1997, MacEachren and Visualization) 1998) – see color plate 2 for examples of interactive controls.



color plate 2. Interactive controls for dynamic maps. The top control panel is from the Earth System Visualizer, an interactive environment designed to support earth science education. Users can select which variables to display and can start, stop, and step and animation using typical VCR-like controls. In addition, users can “focus” in on a temporal subset (using the tabs on the linear legend) and “brush” selected times of day from the time cycle. In the screen snapshot, the user has limited the animation to five of the seven days for which data are available (with the focusing tool). For more detail, see: www.geovista.psu.edu/publications/harrower/ICA99.html. The bottom control panel, from an environment for exploration of weather patterns, illustrates use of a “time wheel” active legend that depicts the time of day (with color fill in the wheel) and the date (with a particular hue). The user can click on a time of day and the map display will change immediately to that time. Then the user can click on the date and compare the situation at that time of day across the dates. For more detail on active legends, see: www.itc.nl/~kraak/legends/.

Thus, geovisualization is not a passive process of either seeing or reading maps. It is an active process in which an individual engages in sorting, highlighting, filtering, and otherwise transforming data in a search for patterns and relationships. It is possible to find many parallels between developments in the 1990s directed toward geovisualization and Bertin’s perspective on “graphics and graphic information processing,” originally presented more than twenty years ago. His contention that the “aim of graphics” is “a higher level of information” is at the core of some of my own ideas about visualization as a tool for “knowledge construction.”

Bertin’s “graphic constructions,” the means by which he proposes to achieve this higher level of information, correspond in fundamental ways to methods developed subsequently in EDA, information visualization, and geovisualization (e.g., Mackinlay 1986, Monmonier 1989, Buja et al. 1991, Cook et al. 1995, Haug et al. 1997, Inselberg 1997, Card, Mackinlay, and Shneiderman 1999). As Bertin points out in this issue, the advent of computerization did not result in immediate implementation of his core ideas about searching for patterns and relationships through matrix manipulation, although computerization was attempted in his laboratory. More recent work, however, by Adams (1991) and by

Gluck, et al., (1999) has been successful in implementing some of the matrix manipulation approach.

This brief essay does not allow for a comprehensive (or even a cursory) review of work in geovisualization (or EDA or information visualization) nor even of the relationship of this work to Bertin's pre-computer approach to geographic information processing. Instead, I provide one example from research in which I am involved. The research is directed to developing visual methods for knowledge construction using highly interactive tools that relate in several ways to Bertin's pre-computer graphic information processing approach.

As part of a larger research project (www.geovista.psu.edu/apoala/index.htm), Robert Edsall (1999) has developed and implemented an interactive parallel coordinate plot (PCP) for exploring multivariate data (figure 2). A PCP is a graphic device that applies the graphic variable of location to depict data elements along a series of parallel axes, each of which represents a single data variable (Bolorforoush and Wegman 1988, Inselberg 1981, Inselberg et al. 1994). Line segments connect a data entity's position on adjacent axes, with the shape produced by the set of segments for a particular entity serving as a "signature" for the entity that can be compared to others. Entities with similar signatures can be considered similar in multidimensional space. In Edsall's web-based implementation (http://www.geovista.psu.edu/storage/edsall/Tclets072799/tclet_home.htm), the variables mapped to each axis can be assigned (and reassigned) by the user. This allows users to reorder axes and group variables together so that positive or negative relations between variables are highlighted (seen as parallel or crossed lines joining adjacent axes, respectively). This reordering feature is analogous to many of Bertin's matrix manipulation and sorting ideas.

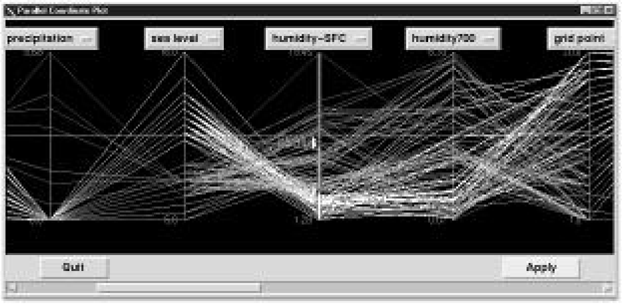
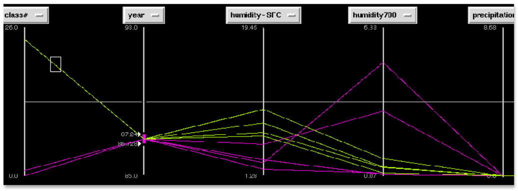
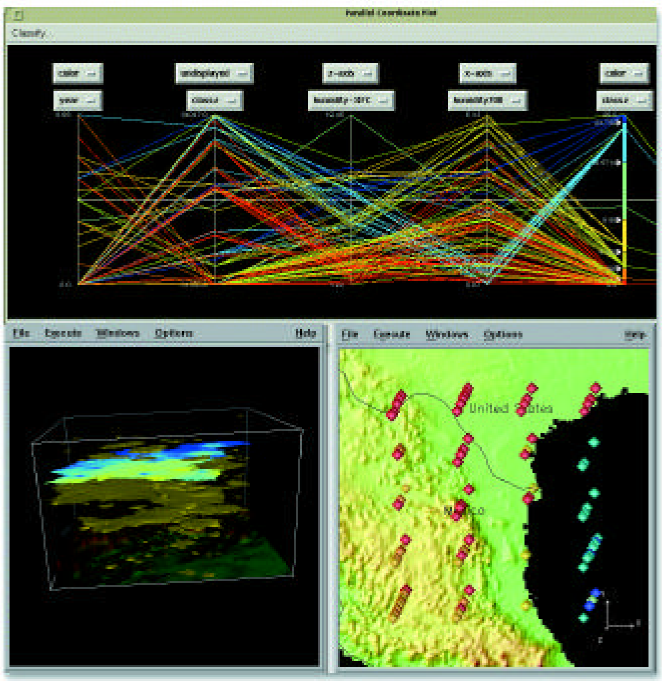


figure 2. A dynamic parallel coordinate plot (PCP). In this particular instantiation, the user has assigned a set of climate variables to each axes of the PCP, grouped data entities into classes based on their surface humidity values, and assigned a sequential color scheme to the result (reproduced here as a gray tone range). The crossed lines between the sea level pressure and surface humidity axes indicate an inverse relationship between these two variables.

In addition to reordering variable axes, Edsall's PCP implementation allows the user to classify data on a selected variable, and represent the classes using one of several logical color schemes (derived from Brewer's color syntactics, see: (Brewer 1994)). More detailed analysis of the PCP and be accomplished through "brushing" (highlighting entities, lines of the PCP, that the user selects directly by pointing at them on the screen) or "focusing" (narrowing the set of lines displayed to a small subset that depict entities having similar values on one variable) (color plate 3). The dynamic PCP has proved to be particularly effective when linked, dynamically, to other depictions of high-dimensional output from a data mining operation (MacEachren et al. 1999) – see color plate 4. One of our next steps is to link the PCP to small multiple maps, allowing users to reorder the PCP axes with the small multiples rearranged to match, or to reorder the maps with the PCP axes correspondingly rearranged. This idea has its roots in Bertin's discussion of methods for analyzing raw materials for the U.S. chemical industry (Bertin 1981, p. 158-159).



color figure 3. Focusing and brushing applied to a PCP. With *focusing*, the user manipulates the attribute range within which data are depicted, with the data in this example being a sample from a much larger set that are prototypical of classes produced by a data mining run. In the figure, focusing is applied to the year axes by selecting that axis and moving tabs to define a one-year range of data, with all data for other years hidden as a result. For this year, prototypical data entities fall in three of the data mining classes. *Brushing* is then applied to class 24, highlighting the entities in that class in bright green. All have zero precipitation, low 700mb humidity (between the rates for the other two classes), and moderate surface humidity (higher than for the other two classes). The data mining tool used here was AutoClass, public domain software that provides unsupervised classification of large high-dimensional data sets using methods based on Bayesian statistics.



color plate 4. A set of dynamically linked representations of the output of a data mining run that attempts to extract multidimensional categories from a set of climate data. User manipulation of the PCP at the top of the screen is reflected in two depictions that represents location (in X and Y) and time (in Z). The view on the right depicts classed data points in time and space resulting from the data mining run. The blue points over the Gulf of Mexico indicate that all these off-shore locations were grouped in the same class. The view on the left depicts the raw precipitation data in time and space (with green isosurfaces) and the temperature distribution across space at one point in time (with the shaded isarithmic layer).

I believe that many of the graphic information processing ideas originally persented by Bertin (1981) were ahead of their time. They were not adopted quickly because they were hard to implement using manual methods. We now have the technology to try Bertin's suggestions, assess them, and extend them in many ways. In addition, however, changes in technology present many opportunities that were not foreseen by Bertin, opportunities that pose exciting challenges as we strive to take visual information analysis to a new level. I close, therefore, with a brief characterization of a few such challenges.

GeoVisualization challenges for the next decade

The International Cartographic Association Commission on Visualization and Virtual Environments, which I chair (with Menno-Jan Kraak as co-chair), is developing a series of white papers that outline a research agenda for the next decade (see: www.geovista.psu.edu/ica). That effort involves collaboration among researchers from several disciplines and countries, and is impractical to summarize here. Instead, I will highlight three challenges that I think are particularly important to address, and that relate directly to the cognitive-semiotic approach to representation that I advocate. These challenges are informed by work of the ICA Commission, but do not necessarily reflect the consensus that is being developed by that group. They are driven by changes in both technology and society. These include: dramatically increasing volumes of geographic information, growing awareness of the role of this information in addressing problems that are important for science and society, and advances in visual representation and telecommunications technology that extend the ways in which available geographic information can be used.

Developing a typology of operations for georepresentations and a syntactics for their use

Bertin's approach to fundamental *graphic variables* and their application was developed for static representations, with several authors developing typologies (what I call syntactics) that define appropriate matches between kinds of data and graphic variables. As noted above, the approach has been extended to dynamic representations with delineation of fundamental *dynamic* and *sonic variables* and rules for their application. What is missing, in the context of today's highly interactive representation forms, is a corresponding delineation of fundamental *operations* that a user might apply to an interactive map or related graphic. An "operation" here, is considered to be a user initiated action that causes some feature of the map display to change. Examples are the use of brushing and focusing, mentioned above, to manipulate the portion of the display or data range that is emphasized. Such operations, once a more complete set is identified, should be matched with guidelines on their appropriate application.

As an anonymous reviewer pointed out, it is possible to identify operations on maps that do not require interactive maps (sketching the location of a proposed object, such as a road); and we do not have a base of knowledge concerning these operations to build from. A logical starting point for work to address the research goal of formalizing our approach to map operations might be Bertin's own concept of "graphic constructions" that, by their nature, assume user manipulation of graphics (with a particular emphasis on reordering matrices). For initial discussion of possible typologies of operations, see (Keller and Keller 1992, Qian et al. 1997).

Balancing abstraction and realism in GeoVirtual environments

Many developments in the history of cartography, particularly those of the past half century stimulated by Bertin, Robinson (e.g., Robinson 1952, Robinson 1982), Jenks (e.g., Jenks 1970, Jenks 1976), and others have lead to increasingly abstract representation forms for maps. In contrast, research in computer graphics has focused on generating increasingly realistic displays, with a current focus on virtual environments that add behaviors and sounds to enhance visual realism. Cartography can point to centuries of successful abstraction that makes the world easier to understand as support for its emphasis on abstraction. On the other hand, computer graphics can point to the evolution of perception and cognition to deal with a detailed three-dimensional dynamic world as support for its emphasis on creating increasingly detailed three-dimensional display. The real challenge, however, is not to determine which of these perspectives is "correct," but to understand the relative advantages of abstraction and realism for different problem contexts, users, and kinds of information representation – and to explore the potential that technology now offers for combining abstract and realistic representation in a single *GeoVirtual* environment. A starting point for considering these challenges can be found in (MacEachren, Kraak, and Verbree 1999, Verbree et al. 1999, MacEachren, et al. in press).

Facilitating different-place collaboration

Most research directed to graphic information processing or geographic visualization has focused on concepts, methods, and tools applicable to visual data exploration by individuals working alone. Many scientific, instructional, or decision making situations, however, involve interaction or collaboration among groups of individuals. At the same time, telecommunications technology has made it possible to consider collaboration among individuals working in different places at either the same time (synchronously) or at a different times (asynchronously). For background on collaborative environments for geospatial information analysis, see (Churcher and Churcher in press, MacEachren in press).

A significant challenge exists if we are to meet the need for visual analysis methods suited to group use and take advantage of telecommunications technology that can enable groups to consist of individuals in different places. A few of the cognitive-semiotic issues that should be addressed include: how to represent participants in the collaboration, how to represent their behaviors, and how to represent each participant’s perspective on the problem to the other participants (both the spatial viewpoint from which participants are observing the display and the conceptual or disciplinary viewpoint from which interpretation is made, thus from which meaning is applied). A particular challenge, related to sharing of perspectives, involves developing methods that enable transitions between representations (and perspectives) to be made (without disorienting the user) and that allow the user to understand how the varied perspectives (theirs and their collaborators) relate to one another.

Discussion

The three challenges outlined above, of course, are only a subset of those that will demand attention. Other important components of a geovisualization research agenda for the next decade include the difficult but critical problems of merging geovisualization methods with geographic information systems, developing integrated visual and geocomputational analysis tools, integrating intelligent agents into visual displays, and others. Meeting the range of challenges sure to arise will require cartographers and geographic information scientists to collaborate with others from many fields, including but not limited to computer science, telecommunications, information design, information visualization, cognitive psychology, cognitive science, and semiotics.

Rapid advances in technology promise dramatic improvements in methods for visual representation and analysis of geospatial (and other) information. Considerable research energy is likely to be spent in simply adapting the technology for use in geospatial information representation and analysis. It is essential, however, that we not become so enamored with technology that we lose site of our goals for geospatial information representation or of the solid conceptual basis for representing and analyzing that information developed by Bertin and others.

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