Thinking in the Context of Seeing
: Geographic visualization, cartography, and GIS [*]

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Abstract : Recently, geographic visualization is gathering much attention as a method to expand the realm of geographic analysis. This paper presents a comprehensive review of the contributions in the literature that can be applied to geographic visualization and provides a proper context within which the implications on geography can be examined. Discussion starts out with the rapidly emerging field of scientific visualization (SV) and examines how it fundamentally changed our way of dealing with data. The contributions from exploratory data analysis and dynamic graphics are then examined. Finally, the studies in the field of cartography and geography that have contributed to developing various visual analytical methods and geographic visualization are reviewed.

Key Words: scientific visualization, exploratory data analysis, dynamic graphics, cartographic visualization, geographic visualization

요약 : 최근 들어 지리적 시각화 기법이 지리적 분석의 영역을 확장할 수 있는 하나의 방법으로 많은 관심을 끌고 있다. 이 논문에서는 지리적 시각화에 관련된 다양한 연구들을 종합적으로 검토하여 시각화 방법이 지리학에 미치는 영향에 대한 논의가 이루어 질 수 있는 맥락을 제공하고자 한다. 우선 새롭게 부상하고 있는 과학적 시각화에 대한 논의를 통해 시각화가 어떻게 자료를 처리하고 분석하는 방식에 근본적인 변화를 가져왔는가를 검토하였다. 이어서 탐색적 자료 분석과 동적 그래픽스라는 두 분야가 시각화 방법의 발전에 어떤 기여를 하였는가를 살펴보았다. 마지막으로 지도학과 지리학 분야에서 시각화 방법을 발전시키는 데 기여한 연구들을 고찰하였다.

주요어 : 과학적 시각화, 탐색적 자료 분석, 동적 그래픽스, 지도학적 시각화, 지리적 시각화

I. Introduction

Due to the enormous improvement in data collection and management technology, more and more spatial data are being collected every day. Not only is the volume of the collected data growing exponentially, but the information included in the data collection process is getting more and more detailed and diverse. Take, for example, the 911 calls generated every day in the U.S. Throughout the United States, each call that comes in is time-stamped, the location mapped,

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and the nature of the emergency recorded. For researchers interested in examining the spatial and temporal patterns and the underlying causes for creating the patterns in these emergency calls, this kind of detailed information can provide a tremendous research opportunity. However, another direct consequence of this data explosion is that much of the information being collected is simply wasted because, in most cases, we do not have adequate tools to undertake the challenge of analyzing and extracting useful information. Without a proper way of analyzing it, all we can do when confronted with the enormity of the data is simply 'warehouse' it.

Geographic Information Systems (GIS), defined as complex, integrated computer systems for the input, storage, retrieval, manipulation, analysis, and display of spatially-referenced data (Marble, 1984), is a perfect tool for handling spatial data. Ideally, GIS should not only be able to help researchers organize and manipulate the data but also provide users with a powerful set of tools for analysis. Unfortunately, the analytical subsystems of current GIS packages do not provide the adequate means to fulfill this requirement. The lack of analytical functions in GIS, both in theoretical perspective and implementations, has been widely regarded as a fundamental weakness of the current state of GIS (Fotheringham and Rogerson, 1994). For GIS to meet the demand for analytical tools, more and more analytical functions must be incorporated into GIS. This can only be accomplished through the rigorous application and implementation of available techniques as well as the development of new analytical methods within the context of spatial data analysis.

There have been significant efforts made to alleviate this 'data-rich, analysis-poor' situation by adopting new developments in the fields of scientific visualization (SV) and exploratory data analysis (EDA) to the realm of GIS. Most notable of these efforts is the series of studies conducted at The Ohio State University. For instance, Sandhu (1990) tackled the visualization problem of very large space-time data by combining EDA and SV techniques in the analysis of global earthquake data. A prototype visualization system for the analysis of large spatial flow data has also been created by Gou (1993). For point data visualization, Hong (1997) has developed an interactive visualization system that can facilitate the visual analysis of the spatio-temporal point patterns.

Given the recent attention to the emerging field of geographic visualization especially in cartography and GIS, this paper intends to present a comprehensive review of the contributions in the literature that can be applied to geographic visualization and to provide a proper context within which the implications on geography can be examined.

II. Scientific Visualization and Visual Information Processing

1. Defining Scientific Visualization

Improvements in data-gathering technology in recent years have effectively put us in the situation where the amount of the data gathered from various sources far exceeds our capability to analyze them. Likewise, the amount of geographic information that will become available in the future is expected to grow exponentially. For example, image data from EOS remote sensing

satellites is expected to accumulate at a rate of one terabit (10^{12} bits) per day (Soffen 1990, quoted from DiBiase et al. 1992). Clearly, scientists and engineers needed a new method of data analysis, and from this need, the field of scientific visualization emerged.

Visualization has been called the second computer revolution (Friedhoff and Benzon 1989). The National Science Foundation report on Visualization in Scientific Computing (ViSC) (McCormick et al. 1987, p. 3) defines visualization as:

"... a method of computing. It transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualization offers a method for seeing the unseen."

While visualization encompasses a wide range of research areas and topics such as computer graphics, image processing, computer vision, computer-aided design, signal processing, and user interface studies (McCormick et al. 1987), a consistent and coherent emphasis has always been on its role as an enabling technology that facilitates the perception, use, and communication of visual information.

2. Scientific Visualization, Cartography, and GIS

In dealing with spatial and even non-spatial relationships, geographers are most comfortable with a depiction that allows them to visualize relationships and connections (MacEachren 1992). In the realm of geographic information systems, visualization encompasses the historical discipline of cartography as well as the emerging fields of scientific visualization and information science

(Clapham 1992). The definition offered by Buttenfield and Mackaness (1991, p. 432) identifies three different aspects of visualization: computational, cognitive, and graphic design. Their definition of visualization is:

"...the process of representing information synoptically for the purpose of recognizing, communicating, and interpreting pattern and structure. Its domain encompasses the computational, cognitive, and mechanical aspects of generating, organizing, manipulating, and comprehending such representations."

Recently, visualization has been drawing more and more interest from geographers and cartographers, which has culminated in a special issue of Cartography and Geographic Information Systems on Geographic Visualization (MacEachren and Monmonier 1992). Indeed, the works of geography and cartography have a great deal of traditional and natural interest in visualization. After all, maps are one of the oldest forms of visual tools to abstract, analyze and communicate spatial information. However, visualization, particularly in the form of maps in GIS, has not taken full advantage of developments in cartographic representation and communication research.

Computer-assisted geographic visualization is fundamentally different from traditional analog cartography that is bounded by what Goodchild (1988) called "pen and paper technology." Digital technology provides us a whole new way of dealing with spatial information by freeing the visualization process from the limitations of pen and paper technology. Some of the possible venues this enabling digital technology opens up include: the direct depiction of movement and change,

multiple views of the same data, user interaction with maps, realism (through three-dimensional stereo views and other techniques), false realism (through fractal generation of landscapes), and the integration of maps with other graphics, text and sound (MacEachren and Monmonier 1992).

3. Visual information processing

The renewed recognition of the power of human visual information processing

Human vision, despite its extremely efficient capability to detect subtle patterns and changes in complex subjects, has not been widely recognized as an 'analytical tool' for data analysis. However, as the amount and the dimension of information that needs to be processed and analyzed increased, and as the inadequacy of the numerical approach to these complex data became more and more apparent, visual analysis utilizing natural human visual information processing capability emerged as one of the powerful tools to be used in the analysis. Graphics can store enormous amounts of data in a very compact form and be presented in a manner in which many hidden relationships among variables can be easily recognized. As Tufte (1983) succinctly and aptly put, 'graphics reveals data.' Therefore, when complex data are presented in graphical forms, in many instances it is surprisingly easy to recognize underlying patterns by simply looking at it. As we can see in the following quote from Tufte (1990, p. 50), we use our visual information processing ability all the time in our everyday life:

'We thrive in information-thick worlds because of our marvelous and everyday capacities to select,

edit, single out, structure, highlight, group, pair, merge, harmonize, synthesize, focus, organize, condense, reduce, boil down, choose, categorize, catalog, classify, list, abstract, scan, look into, idealize, isolate, discriminate, distinguish, screen, pigeonhole, pick over, sort, integrate, blend, inspect, filter, lump, skip, smooth, chunk, average, approximate, cluster, aggregate, outline, summarize, itemize, review, dip into, flip through, browse, glance into, leaf through, skim, refine, enumerate, glean, synopsize, winnow the wheat from the chaff, and separate the sheep from the goats."

Visual inspection of data can not only provide a means to quickly detect patterns, but also provide a possible line of further investigation to reach a cause and effect relationship among depicted data. Probably the most well known example of simple graphic presentation of data leading to the discovery of an ultimate cause and effect relationship is the map created by Dr. John Snow regarding the spread of the cholera in central London in September, 1854 (Tufte 1983). He plotted the cholera deaths with dots and also marked the area's 11 water pumps (Figure 1). Upon inspection of the plotted data, Snow found that cholera occurred almost entirely among those who lived near and drank from one of the water pumps (specifically, the Broad Street water pump, which is located in the center of the map). By having the pump's handle removed, he could stop the epidemic, which cost more than 500 lives *

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* Tobler(1994) wrote a BASIC program showing Dr. Snow's map and Thiessen polygon boundaries around the pumps. It was developed for a student exercise in a course "Teaching Introductory Geographical Data Analysis with GIS" and shows how effective Dr. Snow's map is in introducing the power of graphical analysis.

Abstract analytical thinking vs. visual thinking

Vision is efficient because it produces abstractions from the complex input to the system. This ability to produce abstractions through vision comes before conscious (i.e., logical) processing of the information (Arnheim 1969; Friedhoff and Benson 1989). The primary advantage of visualization is that envisioning is a process of abstraction. As MacEachren and Ganter (1990) put it, "The mind's strengths are in simplification, approximation and abstraction" (p.67). There are two distinct but related activities involved in visualization: visual thinking and visual communication. According to DiBiase et al. (1992, p. 201):

> "Scientists are engaged in visual thinking when their intent is to produce new knowledge and their method involves creating and interpreting graphic representations. When their intent turns to distributing existing knowledge in an unambiguous graphic form, they are engaged in visual communication."

It is well known that each side of the human cerebral hemispheres (two sides of the brain) are related to different mental functions. The monitoring of brain waves in the right and left hemispheres while the subject performed different tasks (Ornstein 1973) provides evidence that not only do the functions of the left and right sides of the brain differ markedly, but that both sides of the brain are also involved in highly complex cognitive functioning. The left hemisphere mode is verbal, objective, analytic, linear, symbolic, logical, rational, abstract, temporal, and digital; the right hemisphere mode is visual, holistic, spatial, analogic, concrete, synthetic, intuitive, nonrational, and nontemporal (Muehrcke 1980).
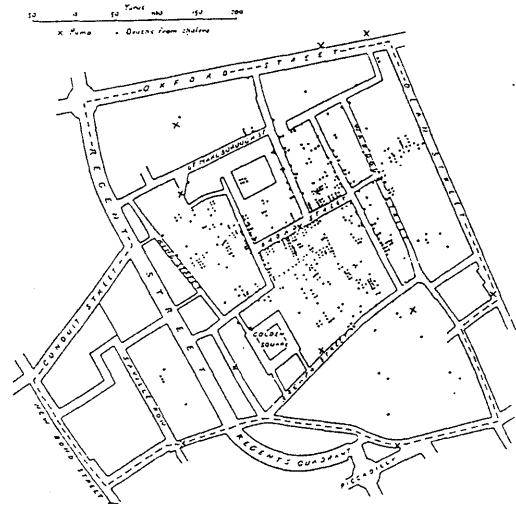

Figure 1 Dr. John Snow's map of the spread of cholera in central London in Septemder 1852. Deaths are marked by dots and water pumps by crosses.
The contaminated pump is located on Broad Street. (Source: Tufte 1983).

Unfortunately, scientists have largely ignored the mental functions of the right hemisphere of the brain in favor of the more verbal and numerical left side in their approach to analyses. For centuries, analytical thinking, which involves the mental faculties closely related to the brain's left hemisphere, has been encouraged and emphasized. At the same time, the faculties related to the right side of the brain, the visual and intuitive side, have been regarded as vague and subjective, and therefore unreliable for rigorous scientific activities. However, researchers have shown that although each half of the brain deals with reality in its own way, both appear to use high-level cognitive modes which involve thinking, reasoning, and complex mental functioning (Muehrcke 1980). For creative thinking to occur, both sides of the brain need to work in concert. In other words, visual thinking complements abstract

thinking.

Thinking visually means developing the cognitive skills related to the right side of the brain. It means realizing that "thinking can occur in other than verbal and mathematical modes. Sensory modes of thought, especially the visual mode, are at the very heart of thinking" (Muehrcke 1980, p.10). Visual images are fundamental in information processing regardless of the nature of the reality we are dealing with. Whether it be a physical reality, or the relationship among multiple variables, or a complex mathematical concept, if we can visualize it, it is much easier to understand and can possibly lead us to an insight.

Muehrcke (1980) classified visual images into the following three types: seeing, imagining, and graphic ideation (idea sketching). Seeing is not mere sensory information gathering. It is a creative and active cognitive process. We think as we see things. Muehrcke gives us Watson's account of the discovery of the double helical structure for DNA as an example of thinking in the context of seeing. The second type of visual image, imagining, has to do with what we construct in our mind's eye. Dreams are a typical example. Like thinking in the context of seeing, the "flashes of insight" (Muehrcke 1980, p. 12), generated from the subconscious can also lead to great discoveries. The third type, graphic ideation or idea sketching, is what we generally do when we want to organize ideas. Rough sketching of ideas help organize and clarify our thoughts. Drawing graphic images itself is part of the mental process. In Muehrcke's (1980, p.13) words, "idea sketching acts as a mirror to reflect the visual mind." The following quote from MacEachren et al. (1992, p. 99) sums up the fundamental role of visual thinking in information processing within the context of geography:

> "Even when dealing with nonspatial relationships, geographers are most comfortable with a depiction that allows them to visualize the relationships and connections that in turn lead to hypotheses about underlying causes for the patterns that become apparent when data are presented in a spatial format."

With both spatial and nonspatial relationships, the envisioning process therefore requires us to perform certain mental operations to form abstracts. Table 1 shows the mental operations specifically related to this visual mode.

The proper exercise of these visual-spatial operations can be facilitated through the use of tools that help us display the visual images of the things that we are interested in. At the simplest level, pen and paper can be used to plot the image. Paper maps are a perfect example of a visualization tool that helps to identify abstract spatial relationships existing among physical entities. Imagine how we would deal with geographic space if there were no maps. As the nature of the data and the relationships among objects get more complex, the tools that assist mental operations need to be more diverse and dynamic. It is from this necessity that we try to develop new visualization techniques and tools that are tailored to the specific nature of the data with in which we are concerned.

Table 1. Spatial-Visual Operations (after Muehrcke 1980).

1. PATTERN SEEKING

   (a) Closure

      * filling-in an incomplete pattern

      * finding a target figure imbedded in a more complex image

   (b) Matching one pattern with another as wholes, or a detail-by-detail comparison of two or more patterns

   (c) Categorizing—distinguishing objects by recognizing common features. The way we literally invent our world.

   (d) Pattern completion by interpolation/extrapolation

2. VISUAL MEMORY

   Ability to retain visual imagery through a combination of vigorous perception and faithful remembering. Key to cognitive mapping.

3. ROTATING IMAGES

   Mentally rotating an object in its environment or rotating the point-of-view (viewpoint) in relation to the object.

4. DYNAMIC STRUCTURES

   Moving a single object in space or moving several objects in relation to each other. Examples: folding/unfolding operations; tie/untie knots.

5. VISUAL REASONING

   Moving from concrete to abstract images (visual induction) or from abstract to concrete images (visual deduction).

6. VISUAL SYNTHESIS

   A creative putting together of parts to form a greater whole. Involves manifold operations.

Ⅲ. Exploratory Data Analysis

1. Definition

The course of scientific investigation can be classified into two broad stages: the exploratory stage and the confirmatory stage (Young et. al. 1988). In the exploratory stage, scientists examine data without *a priori* notion to form hypotheses, which are then tested in the confirmatory stage. Until recently, most of the attention in analysis was given to the confirmatory stage while the importance of the exploratory stage was largely ignored. Hypotheses were mostly generated based on 'hunches' —although in many cases highly plausible hunches stemming from the analyst's thorough knowledge of the subject. This lack of emphasis on the hypothesis-forming stage of scientific investigation was exacerbated by the lack of proper methods and tools to support such activities.

This situation was fundamentally changed by the development of a new analytical method called exploratory data analysis. Tukey (1977, p. V), in his landmark book *Exploratory Data Analysis*, states that EDA:

"is about looking at data to see what it seems to say. It concentrates on simple arithmetic and easy-to-draw pictures. It regards whatever appearances we have recognized as partial descriptions, and tries to look beneath them for new insights. Its concern is with appearance, not with confirmation."

In his effort to define EDA more precisely, Good (1983) emphasized the importance of hypotheses formulation with the use of EDA. Basically EDA is a matter of looking for patterns that "we never expected to see (Tukey 1977, p. vi)." According to Good (1983), EDA contributes to two aspects of scientific discovery. One aspect is what he calls "successive deepening," a process in which a hypothesis is formulated and, if it explains enough, is judged approximately correct. Then the results

are used to improve it. Examining residuals or treating them as if they were original data in EDA is a good example of this approach.

The other aspect of scientific discovery to which EDA contributes is the use of "divergent thinking", or the avoidance of mental ruts. EDA emphasizes looking at data from several points of view, thereby exposing hidden or unexpected patterns in data. This helps us to ask new questions, leading to the development of new hypotheses. As Tukey (1980, p. 24) aptly put it, "Finding the question is often more important than finding the answer." In light of this, Good's (1983) list of five aims of EDA is worth noting. They are: i) the presentation of data; ii) pattern recognition; iii) hypothesis formulation; iv) to look for hypotheses of greater explicativities; and v) to maximize expected utility allowing for the guessed costs and delays of computation and thinking. What is consistent throughout these five aims is the emphasis on the use of graphics, pattern finding and hypotheses formulation. They are the essence of EDA.

2. EDA and spatial analysis in GIS

Why is EDA important to GIS? While there is a notion that Geographic Information Systems are distinguished from automated cartography by their "emphasis on analysis (Goodchild 1987, p. 333)," the lack of analytical capabilities in GIS has been one of the main concerns of GIS researchers and users (for a comprehensive treatment of this topic, see Fotheringham and Rogerson 1994). The problem of incorporating spatial analytical tools into GIS to allow more rigorous and sophisticated analyses has been approached in various ways. Goodchild et al. (1992) classified four types of

links that can exist between GIS and spatial analysis: i) stand-alone spatial analysis software; ii) loose coupling of existing GIS software with statistical software (either standard packages or purposely written); iii) close coupling of GIS software with spatial statistical software; and iv) full integration of spatial analysis with GIS. Although not included in the above classification, expanding the analytical functions in existing commercial GIS (e.g., Network module in ARC/INFO, see ESRI 1992) is also a viable option. Efforts made in the 'coupling' approach include linking GIS to existing statistical packages (e.g., Ding and Fotheringham 1992) and embedding spatial modeling into existing GIS (e.g., Batty and Xie 1994). In contrast to these more or less 'loosely coupled' approaches, some researchers have developed more 'tightly coupled' packages allowing dynamic linkages between GIS and the mapping of spatial relationships (e.g., Haslett et al. 1990). On the other hand, others have suggested that a whole new line of spatial analysis methods which are suitable for GIS environment be developed (Openshaw et al. 1987; Openshaw 1994).

Differences in approaches aside, however, it is generally agreed in the discussions on developing spatial analysis tools in GIS that general data exploratory methods would be of great value within GIS. Several years ago, Walker and Moore (1988, p. 348) suggested that the state-of-the-art GIS is "superbly useful for extracting and describing...[spatial data]" but GIS "sorely lacks... routine capabilities...for developing hypotheses about spatially varying feature attributes." Their statement is still valid as far as the analytical capabilities of GIS are concerned. To remedy the

situation, we need to develop more and more diverse and innovative analytical methods and integrate them with GIS. As Openshaw (1994, p. 83) remarked, "Techniques are wanted that are able to hunt out what might be considered to be localised pattern or 'database anomalies' in geographically referenced data but without being told either 'where' to look or 'what' to look for, or 'when' to look." In his discussion on spatial analysis and GIS, O'Kelly (1994) also emphasized the importance of EDA as the tool of choice of spatial analysts especially when they are confronted with large data sets that are generated in large models and GIS. He stated that "The key technical advance will be in pattern recognition, which intelligently allow the user to sift through the data, reduce dimensionality, find patterns of interest, and then order the GIS to find other instances or similar occurrences" (O'Kelly 1994, p. 74).

Some argue that entirely new and different analytical methods for these types of pattern searching and hypotheses generation be developed (most notably, Openshaw et al. 1987). Others contend that we can learn a lot from applying exploratory data analysis methods developed in mainstream statistics (for example, see Haining 1990). Most likely, the problem at hand (the size and dimensionality of the data, and the intent of the research) will dictate which approach is most appropriate for each specific case. Whatever approach we may adopt, however, the more tools we have, the better off we will be.

Ⅳ. Dynamic Graphics and Spatial Data Analysis

1. Dynamic Graphics and Data Analysis

We can substantially increase the efficiency of the graphical methods described above by creating a dynamic system in which the analysts can interact with the graphics. Dynamic environments are important for the analysis of complex, multidimensional data since the addition of dynamic capabilities to traditional static display greatly increase the power of graphical method. As Huber (1983) aptly noted: "We see more when we interact with the picture—especially if it reacts instantaneously—that when we merely watch." An excellent overview of dynamic graphics and available methods is given by Becker et. al. (1987). They recognized two important properties of dynamic graphics: direct manipulation of graphical elements on a computer graphics screen; and a virtually instantaneous change of elements in graphics. In a dynamic graphical environment, the data analyst takes an action through manual manipulation of an input device and something happens, virtually instantaneously, on a computer graphics screen. The analyst can therefore instantly see the result of his action: be it to identify data points with extreme values (labeling) or to change certain parameters of the system. The instant graphic feedback of direct data manipulation helps the analyst easily test various hypotheses or 'explore' other possible lines of investigation which otherwise would require multiple steps and would be clumsy to say the least.

In recent years, the combination of rapidly declining computer hardware costs and increased computing power of personal computers has resulted in many affordable dynamic data visualization packages that can be utilized in virtually every aspect of scientific research. There

is no doubt that this trend will continue, and we can expect that dynamic graphics will be used more and more frequently by scientists dealing with complex multidimensional data.

2. Dynamic Graphics for Spatial Data Analysis

Dynamic graphical methods has amassed significant interest not only in the aspatial domain but also in the spatial domain. What makes spatial data distinct from other data is that spatial data has an alternative key to access the data. In other words, the data can be accessed either by attribute or by location. Location is based on two continuous dimensions (x, y). There can be a multiplicity of possible conceptual data models for spatial data. In addition, spatial data has a distinctive feature of spatial dependence, the propensity for nearby locations to influence each other and to possess similar attributes (Goodchild et al. 1992). These characteristics of spatial data add much complication to the development of dynamic graphics methods for it. By the same token, the characteristics, especially the inherent multidimensionality of spatial data and its spatial dependence, make dynamic graphics methods intuitively natural for spatial data analysis. Given the complexity of designing a system, it is not surprising to observe that there have not been many systems developed in this area. The following section reviews some selected systems.

SPIDER

One of the first attempts to apply dynamic graphics in the context of spatial data analysis was SPIDER (SPatial Interactive Data ExploreR), a system developed by a group in the Department of Statistics at Trinity College in Dublin, Ireland (Haslett et al. 1990; Haslett et al. 1991; Wills et al. 1990). The developers of SPIDER focused mainly on 'multiple spatial views of the data' and 'dynamic linking of statistical and geographical views'. As they put it, "The key to the tool is the dynamic linking of alternative views of data" (Haslett et al. 1991, p. 240). They made a variety of views available to the user: a histogram view, a map view, a scatter plot matrix view, a moving average view, and a trace view. These multiple views are linked to help identify relationships between variables (relationships between data points and their spatial variations and/or relationships among statistical variables). For example, by linking the histogram view and the map view, a user can select a portion of the histogram to identify the locations of the corresponding data points in the map view. Linking is the key in this environment. "Separately the statistical views are of some value, but that value is enormously enriched when the views are linked" (Haslett et al. 1991, p. 235).

SPIDER also possesses an ability to overlay multiple spatial views of the data. For example, satellite image, line coverage, and point data can be overlaid to give the user the orientation of the data. The images in this case, however, are used as a backdrop for the analysis and cannot be operated on. In this aspect SPIDER is more a statistical tool than a GIS. With its well integrated user interface constructed on a personal computer (Mac II), and its innovative way of linking a spatial view of the data to various statistical views, SPIDER provides a good example of how dynamic graphics methods and tools benefit exploratory spatial data analysis.

Polygon Explorer

The idea of applying dynamic graphics to geographic data was also studied by MacDougall (1991, 1992), who examined the possibility of applying commercially available EDA programs to spatial contexts. He also constructed a polygon-based data exploration system called Polygon Explorer. In his study, he first demonstrated the use of commercial software (JMP) to display irregularly spaced point data and raster data for exploratory analysis. These data can be easily imported to EDA programs through JMP's data transformation features. After imported, the data can be displayed as a form of scatterplot (for irregularly spaced point data) or spin plot (for raster data). Multiple linked views are possible for exploration.

For polygon data, MacDougall developed a prototype interface, called Polygon Explorer for the Macintosh computer (MacDougall 1992). This program includes a map display, some basic statistical graphs (bar charts, histograms, and a scatterplot) and a capability for cluster analysis (Figure 2).

These elements in the display are linked together. To further assist exploration, two features are added to the basic display: an ability to transform or re-express a variable to normalize the distribution; and a feature called the "Tukey yard" (following Tukey) or schematic box plot in EDA, which provides a rectangle in the scatterplot to give a visual cue to outliers. Finally, the prototype was used to assess how one widely used statistical analysis (cluster analysis) can be implemented and used in a dynamic graphics environment. As a prototype, this program is quite limited in its data handling capability (one categorical and two

continuous variables) and does not provide extensive analytical functions. However, as the author points out, the initial objective of the prototype was to determine the extent to which dynamic visualization could be achieved for hundreds of polygon data sets. As such, MacDougall's study shows yet another possible research area that can benefit from a dynamic graphics environment.
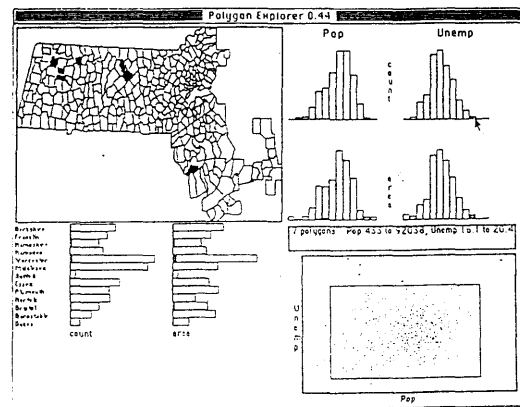

Figure 2 Polygon Explorer display. The display shows towns in Massachusetts with high unemployment. The rectangle in the scatterplot box is the "Tukey Yard." (Source: MacDougall, 1992).

V. Geographic Visualization

The dynamic graphics method is not the only way of visualizing spatial data. In fact, the graphic portrayal of spatial information has been done for centuries by cartographers and geographers. MacEachren (1992) defined geographic visualization as "the use of concrete visual representations— whether on paper or through computer displays or other media—to make spatial contexts and problems visible, so as to engage the most powerful human

information-processing abilities, those associated with vision." In this sense, geographic visualization is nothing new.

However, what sets the new geographic (or cartographic) visualization apart from this long tradition of the graphic portrayal of spatial information is the availability of new tools that can ease the creation of graphics as well as open up new means of portraying the data. With the rapid adoption of GIS in our dealings with spatial data, we are experiencing a rapid transition from the old static medium to the new dynamic medium. As MacEachren and Ganter (1990, p. 67) put it, "More recent development in geographic information systems are providing a testing ground for a variety of new cartographic and graphic tools for scientific visualization. One of the strongest links between cartography and geographic information systems is through cartographic visualization tools and their potential to increase the data synthesis and analysis capabilities of GIS." This section reviews some of the many visualization efforts made in the fields of cartography and geography.

1. Cartographic animation

The traditional emphasis on visual communication in cartography, especially in the search for the 'optimal map,' has prompted some attempts to present the complex nature of spatial data in the form of animation and interactive visualization. Animation, in particular, has been regarded as a way of overcoming the static nature of printed maps and of addressing the dynamic element of change over time. As early as 1959, Thrower (1959) emphasized the potential role of animation

in cartography in terms of visualizing the temporal process and believed that popular animation was just around the corner. A few years later, Cornwell and Robinson (1966, p. 82) investigated the possibilities for computer animated films in cartography, stating that "the prospect for the use of this versatile technique in accomplishing creative dynamic cartography is limited only by the imagination." However, as Campbell and Egbert (1990) pointed out, animated cartography is not much more widespread now than 20 some years ago when Tobler (1970) published the result of the first computer animated map sequence.

Tobler's (1970) well-known computer movie of the urban growth of the Detroit region was the first attempt to utilize the animation technique. In that study, the main purpose of the movie representations of the simulated population distribution in the Detroit region was "to provide insights, mostly of an intuitive rather than a formal nature, into the dynamics of urban growth(Tobler 1970, p. 238)."

The significance of the animation technique in presenting the result of complex spatial data was noted in a series of studies by Moellering (Moellering 1976, 1980a, 1980b). In his study of traffic crashes, he used computer animated film to display the objects of analysis in a dynamic temporal setting (Moellering 1976). He recognized two fundamental uses of animation in geographical settings: one as a cognitive device to facilitate the perception of spatio-temporal dynamics of the process; the other as a heuristic device to aid in suggesting hypotheses. These ideas have been further developed into the 'direct control of animation sequence' (Moellering 1980a) and the

concept of the 'real-time cartographic system' (Moellering 1980b).

It was not until the end of the 1980s, however, that cartographic animation was rediscovered when cartographers recognized the potential of animation for the depiction and exploration of spatial and statistical relationships and patterns (Karl 1992). The subject of the potential benefit of cartographic animation was again brought up by Campbell and Egbert (1990). New animation techniques for spatio-temporal data (Monmonier 1989b, 1990b) and geoscientific processes (DiBiase et. al. 1992) were suggested. In addition, many programs that can be run from personal computers to create cartographic animation appeared on the market (for discussions of some of these programs and design issues, see Gersmehl 1990).

The combination of the renewed attention to and easy accessibility of animation softwares has brought exciting opportunities for cartographic animation. However, many fundamental problems in cartographic animation remain to be solved. For example, there is no consensus on the exact definition of cartographic animation. Many design issues such as symbolization in animated maps, animation speed, legend design, and control of the animation sequence have not been properly addressed. While the studies aforementioned have certainly contributed to broaden the possible use of animation in cartography, they deal only with specific animation techniques for specific cartographic information. More comprehensive studies on the design, perception and production of animated map sequences is needed but not available (Karl 1992).

2. From animation to interactive visualization

The growth in interest in cartographic animation has further expanded into the area of interactive visualization. While animation has been largely regarded as more of an illustrative tool, the interactive visualization system emphasizes the investigative aspect of cartographic visualization. In cartographic animation, we can do one of the following three things: animate space—the process of panning and zooming around and into a large two-dimensional static image; animate time—the map is held still and the action played out upon it; or animate a combination of both (Dorling 1992). Traditional cartographic animation focused primarily on the second method of animation, that is, to record the changes in data through time. Changes are usually represented by either moving the symbols around the map or changing their color. These kinds of representations are suitable to illustrate the points that the producer of the animation wishes to make, but hardly serve to find unknown patterns in the data.

In dealing with visualization of spatio-temporal data, however, this method of animating time continues to be dominant (Gould 1989; MacEachren and DiBiase 1991). Improving upon the technique of sequencing maps to focus the viewer's attention on a meaningfully ordered set of cartographic subpatterns (Slocum et al. 1990), a new animation technique was suggested by Monmonier (1990b). Called 'atlas touring,' this technique involves creating a succession of views through the use of a 'graphic script,' composed using basic sequences called 'graphic phrase' (Monmonier 1989b, 1992). A graphic phrase is a programmed graphic sequence that acts as a building block to construct a graphic script. Using these graphic building blocks, the script developer can put together highly

sophisticated animation sequences that highlight trends or anomalies in the data. As a customized guided tour of complex spatio-temporal data, atlas touring can effectively focus the viewer's attention on the main points of the presentation. The graphic script or atlas touring, however, serves mainly as a narrative tool to communicate complex information in a limited time. Only a limited control of animation (such as pausing to understand a complex scene) is allowed, and the user cannot deviate from the pre-programmed sequences of animation. A truly interactive tool would allow the user to freely roam inside the tour, going back and forth in time, and branching out as he/she finds interesting phenomena in the data even though the existence of such patterns were not foreseen by the script developers.

Animating space, on the other hand, can be much more useful in exploring data. Unfortunately, however, it has been given inadequate attention despite its value and adaptability as an exploratory tool (Dorling 1992). To explore, we need the ability ability to freely search through the data with the full control of its display characteristics: the variables to be examined, the position, color, scale, and aspect of them, and the sequence with which they are chained together. Replacing static maps with a dynamic map means we eliminate hundreds of static maps with various insets and replace them with a single coherent spatial image that can be manipulated at will to suit our needs. In their comprehensive review of animation in scientific visualization, DiBiase et al. (1992) also noted that control over visual variables (position, size, value, texture, hue, orientation, and shape; see Bertin 1983), and dynamic variables (duration, rate of change, and order) are critical to fully exploit the

potential of cartographic animation.

3. Applications of EDA methods to visualization

In developing the interactive visualization systems, many researchers recognized the potential of applying EDA methods and visualization techniques to geographic data (for example, Monmonier 1989a, 1990a; MacEachren and Ganter 1990). As a part of on-going research to develop a methodology for the exploratory analysis of spatio-temporal data, Sandhu (1990) has created a prototype system called the Planetary Data Visualization System (PDVS). This system is special because it deals with a very large volume of global data (earthquake data). Using a supercomputer, the system allows the interactive visualization of global earthquake data with the use of a special temporal symbolization scheme and a basic set of EDA methods.

Noticing that most traditional statistical techniques do not adequately address 'geographic correlation' — the extent to which two variables are similar in spatial pattern—Monmonier (1989a) introduced a technique that he called 'geographic brushing.' Based on a dynamic graphics method called 'scatterplot brushing' (Becker and Cleveland 1987), geographic brushing links a map display to a scatterplot matrix. With the link, the otherwise aspatial display of statistical relationships among variables becomes an efficient means of geographic exploration, raising questions and suggesting hypotheses. This geographic brushing concept can be expanded to incorporate time-series data, making it a temporal brush (Monmonier 1990b), where the user can control the time period for which the data are displayed with a temporal scrollbar. Therefore,

in this high-interaction graphics environment (Becker et al. 1987), a user is equipped with a multitude of tools to conduct the search for meaningful patterns in the data. These tools include statistical tools such as a scatterplot matrix with brushing capability, a tool for spatial relationships such as a geographic brush, and a tool for temporal analysis such as a temporal brush.

4. Multimedia presentation of data

Another way of improving the search process is to use human ability to deal with multiple input modes (text, graphics, audio, and motion video). Multimedia presentation is a good example of reducing the complexity of the overall message by spreading information among several sensory modalities. The explosive growth in multimedia titles in the personal computer software industry certainly demonstrates that multimedia presentation has now become a feasible (and preferred) means of conveying information. Market analysts expect that annual sales of CD-ROM titles will exceed 37 million units by 1995 (Colligan 1994, quoted from DiBiase 1994). One such use of multimedia in cartographic presentation has been reported by DiBiase (1994). As part of the Multimedia Encyclopedia CD-ROM title (New Grolier Multimedia Encyclopedia), 15 animated maps with sound on such topics as the American Revolutionary War, World War II, and Magellan's circumnavigation of the world were produced. Despite various technical roadblocks in designing and producing multimedia maps, DiBiase reports that the process was satisfactory. With apologies to Campbell and Egbert (1990) who stated that cartographic animation is merely scratching the surface, he

declared that "animated cartography is not just scratching the surface anymore (DiBiase 1994, p. 7)."

Simple multimedia, however, does not allow viewers to control the information flow. What they see is predetermined by the designers of the presentation. To overcome this lack of navigational control, the use of hypermedia was proposed (Buttenfield and Weber 1994). Hypermedia has an advantage over simple multimedia in that it links the multiple modes transparently, permitting associative browsing of data. In other words, users can jump directly to the relevant portion of the data for a closer look, and either come back to the previous stage of the data search or follow through the new thread. This kind of capability requires that the tool be 'proactive' (Buttenfield 1993) rather than 'interactive.' While interactivity provides the capabilities to respond to system actions that are anticipated by system designers (through system dialogue boxes and menus), proactive computing simulates a system responsive to commands and queries that may not have been anticipated by system designers (Buttenfield 1993). "When visual tools are proactive, users initiate queries and steer data presentation in a manner consistent with the associative power of the human intellect (Buttenfield and Weber 1994, p. 8)."

The ability to steer data presentation has been recognized as "the most exciting potential [use] of visualization tools" in modeling (McCormick et al. 1987). As an example, Buttenfield and Weber (1994) developed a prototype hypermedia system using a biogeographical database (radial growth in trembling aspens). The system implements cartographic display, as well as statistical graphics

or numeric tabulation. Additional information including text, range maps for North America, and photographic images are available at all times. Animation of aspen growth runs as the default and can be paused. Zooming and panning is possible. With zoom, automatic scale change is performed. Users can follow their own lead to view maps, statistics, text or metadata. In that sense, the system is proactive. However, as the authors point out, it is not fully proactive because it lacks a scripting language for viewers to develop their own links and command structure (Buttenfield and Weber 1994). Nevertheless, their prototype demonstrates the possibility of a whole new breed of geographic visualization systems where the user dictates what the system shows and how the system shows it rather than the system designer dictating what the user sees.

5. Studies in geographic visualization

Since MacEachren and Ganter's (1990) powerful arguments for cartographic visualization, many geographic visualization studies have appeared in the literature. A partial list of studies found in the literature covers a wide range of topics, such as using visualization techniques for environmental modeling, visualization tools for regionalization, and visualization of the spatial structure of the social geography of a nation.

Another research area where the visualization techniques could be proven useful is visualization of spatial data quality. The quality of spatial data and databases has been a major concern for developers and users of GIS (Chrisman 1983). The volume and variety of available spatial data are increasing rapidly. At the same time GISs are

becoming cleverer with an increasing number of automated functions available at the users' fingertips. The ease of use and increasing level of sophistication, however, also increases the possibility of reaching wrong conclusions and poor decisions when the quality of the data and the fitness of the applied model are not adequately understood. Therefore, for a GIS to be used as a true 'spatial understanding support system' (SUSS, see Couclelis 1991), it should be able to represent the quality of the spatial data and the database that the decision is based on. In this regard, visualization can be used as a method for capturing, interpreting, and communicating quality information. Some possible research themes on this issue are found in Buttenfield and Beard (1991) and Clapham(1992).

Ⅵ. Summary and Conclusion

This paper examined the contributions from the fields of scientific visualization, exploratory data analysis, and dynamic graphics to the development of visual analytical tools that can be used for spatial data analysis and geographic visualization.

We started our discussion with the rapidly emerging field of scientific visualization (SV) and examined how it fundamentally changed our way of dealing with data. We then discussed the exploratory data analysis (EDA)—an alternative to the more traditional confirmatory method of data analysis, with the emphasis on the relationship between EDA and scientific visualization and on the way in which EDA relates to the proper construction of a framework for visual data analysis.

EDA relies heavily on visual presentation of data in the search for meaningful patterns. As such, it

is closely tied to scientific visualization. In fact, many SV systems incorporate many EDA methods in their core functions. The nature of EDA as 'detective work' (Tukey 1977) requires viewing data in many possible combinations of angles, dimensions, and projections. Therefore, EDA is invariably dynamic and requires a dynamic environment. Therefore, a review on dynamic graphics followed. Cartographic data representation is inherently visual. Throughout the long history of cartographic production and research, cartographers have developed highly sophisticated methods of visual representation for an enormous amount of spatial and aspatial information. Recently, much effort has been made to free cartography from the limitation imposed by its traditional medium of choice, namely, printed maps and their 'static' nature. While the need for and the great potential of more 'lively' maps was recognized early on (see Thrower 1959), it was not until recently that much advancement in making maps more dynamic has been made. At the root of these newly invigorated activities, of course, is the explosion of computer technology and its inevitable incorporation into cartographic methods and production.

As we have seen in this paper, the power of human visual information processing should be recognized and its active use in analysis should be encouraged. There are many obstacles in bringing this power into the hands and minds of analysts. Easy and intuitive tools to carry out the visual analysis should be developed. New and improved visual representation methods should also be developed. Being inherently spatial and graphical, geographers can and should play an important role in furthering this new possibility.

References

Arnheim, R.A., 1969, *Visual thinking*, Berkeley: University of California Press.

Batty, M. and Xie, Y., 1994, Urban analysis in a GIS environment: population density modelling using ARC/INFO, In S. Fotheringham & P. Rogerson (Eds.), *Spatial Analysis and GIS*, 190-219, London: Taylor & Francis.

Becker, R.A. and Cleveland, W.S., 1987, Brushing Scatterplots, *Technometrics*, 29(2), 127-142.

Becker, R.A., Cleveland, W.S., and Wilks, A.R., 1987, Dynamic Graphics for Data Analysis, *Statistical Science*, 2, 355-359.

Bertin, J., 1983, *Semiology of Graphics*, (Berg, William J., Trans.), Madison: University of Wisconsin Press.

Buttenfield, B. P., 1993, Proactive graphics for GIS: prototype tools for query, modeling and display, *Proceedings AUTO-CARTO 11*, Minnearpolis, Minnesota, October 1993, 377-385.

Buttenfield, B.P. and Beard, M.K., 1991, Visualizing the Quality of Spatial Information, *Auto-Carto 10*, Baltimore, Maryland: ACSM, ASPRS, 423-427.

Buttenfield, B.P. and Mackaness, W.A., 1991, Visualization, In D. Maguire, M. F. Goodchild, & D. Rhind (Eds.), *Geographic Information Systems: Principles and Applications*, 427-443, London: Longman Publishers Ltd.

Buttenfield, B. P. and Weber, C.R., 1994, Proactive Graphics for Exploratory Visualization of Biogeographical Data, *Cartographic Perspectives*, 19 (Fall),8-18.

Campbell, C. and Egbert, S.L., 1990, Animated Cartography/Thirty Years of Scratching the Surface, *Cartographica*, 27(2), 24-46.

Chrisman, N.R., 1983, The role of quality information in the longterm functions of geographic information system, *Cartographica*, 21(2), 79-87.

Clapham, S.B., 1992, A Formal Approach to the Visualization of Spatial Data Quality, *Proceedings of GIS/LIS '92*, San Jose, California: Vol. 1, 138-149.

Colligan, B., 1994, To the winner goes the standard,

NAB Multimedia News (Winter), 16-17.

Cornwell, B. and Robinson, A., 1966, Possiblilities for computer animated films in cartography, *Cartographic Journal*, 3(2), 79-82.

Couclelis, H., 1991, There is Nothing as Theoretical as Good Practice, *Environment and Planning B: Planning and Design*, 18, 379-384.

DiBiase, D., 1994, Designing animated maps for a multimedia encyclopedia, *Cartographic Perspectives*, 19 (Fall), 3-7, 19.

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 Informatin Systems*, 19(4), 201-214, 265-266.

Ding, Y. and Fotheringham, A.S., 1992, The Integration of Spatial Analysis and GIS, *Computers, Environment and Urban Systems*, 16, 3-19.

Dorling, D., 1992, Stretching Space and Splicing Time: From Cartographic Animation to Interactive Visualization, *Cartography and Geographic Information Systems*, 19(4), 215-227, 267-270.

ESRI, 1992, *Arc/Info User Guide*, Environmental Research Systems Institute, Inc.

ESRI, 1992, *Arc/Info User's Guide: Network Analysis,*, Environmental Systems Research Institute, Inc.

Fotheringham, S. and Rogerson, P. (eds), 1994, *Spatial Analysis and GIS*, Taylor and Francis, London.

Friedhoff, R.M. and Benzon, W., 1989, *Visualization: The second computer revolution,*, New York: Harry N. Abrams, Inc.

Gersmehl, P.J., 1990, Choosing Tools: Nine Metaphors of Four-Dimensional Cartography, *Cartographic Perspectives*, 5, 3-9.

Good, I.J., 1983, The Philosophy of Exploratory Data Analysis, *Philosophy of Science*, 50, 283-295.

Goodchild, M.F., 1987, A spatial analytical perspective on geographical information systems, *International Journal of Geographical Information Systems*, 1(4), 327-334.

Goodchild, M.F., 1988, Stepping Over The Line: Technological Constraints And the New Cartography, *The American Cartographer*, 15(3), 311-319.

Goodchild, M.F., 1991, Spatial Analysis with GIS: Problems and Prospects, *GIS/LIS* '91, Atlanta, GA: Vol. 1, 40-48.

Goodchild, M., Haining, R., and Wise, S., 1992, Integrating GIS and spatial data analysis: problems and possibilities, *International Journal of Geographical Information Systems*, 6(5), 407-423.

Gou. Z., 1993, *Scientific Visualization and Exploratory Data Analysis of A Large Spatial Flow Data Set*, Ph.D. Dissertation, The Ohio State University.

Gould, P., 1989, Geographic Dimensions of the AIDS Epidemic, *The Professional Geographer*, 41(1), 71-78.

Haining, R.P., 1990, *Spatial Data Analysis in the Social and Environmental Sciences*, Cambridge: Cambridge University Press.

Haslett, J., Bradely, R., Craig, P., Unwin, A., and Wills, G., 1991, Dynamic Graphics for Exploring Spatial Data With Application to Locating Global and Local Anomalies, *The American Statistician*, 45(3), 234-242.

Haslett, J., Wills, G., and Unwin, A., 1990, SPIDER - an interactive statistical tool for the analysis of spatially distributed data, *International Journal of Geographical Information Systems*, 4(3), 285-296.

Hong, Sang-Ki, 1997, *Development and proof-of-concept of an interactive visualization system for the spatio-temporal analysis of linear point data*, Ph.D. dissertation, The Ohio State University.

Huber, P.J., 1983, Statistical graphics: history and overview, *Fourth Annual Conference and Exposition of the National Computer Graphics Association*, Fairfax, VA: 667-676.

Karl, D., 1992, Cartographic Animation: Potential and Research Issues, *Cartographic Perspectives*, 13, 3-9.

MacDougall, E.B., 1991, Dynamic Statistical Visualization of Geographic Information Systems, *Proceedings of GIS/LIS* '91, Atlanta, Georgia: Vol. 1, 158-165.

MacDougall, E.B., 1992, Exploratory Analysis, Dynamic Statistical Visualization, and Geographic Information

Systems, *Cartography and Geographic Informatin Systems*, 19(4), 237-246.

MacEachren, A.M., 1992, Visualization, In R. F. Abler, M. G. Marcus, & J. M. Olson (Eds.), *Goegraphy's Inner Worlds*, 99-137, New Brunswick, NJ: Rutguers University Press.

MacEachren, A.M. and DiBiase, D., 1991, Animated Maps of Aggregate Data: Conceptual and Practical Problems, *Cartography and Geographic Informatin Systems*, 18(4), 221-229.

MacEachren, A.M. and Ganter, J.H., 1990, A Pattern Identification Approach to Cartographic Visualization, *Catrographica*, 27(2), 64-81.

MacEachren, A.M. and Monmonier, M., 1992, Introduction, *Cartography and Geographic Informatin Systems*, 19(4), 197-200.

Marble, D.F., 1984, Geographic Information Systems: an overview, *Pecora 9*, Sioux Fall, SD: 18-24.

McCormick, B.H., DeFanti, T.A., and Brown, M.D., 1987, Visualization in Scientific Computing, *Computer Graphics*, 21(6),

Moellering, H., 1976, The Potential Uses of a Computer Animated Film in the Analysis of Geographical Patterns of Traffic Crashes, *Accident Analysis and Prevention*, 8, 215-227.

Moellering, H., 1980a, Strategies of Real-Time Cartography, *The Cartographic Journal*, 17(1), 12-15.

Moellering, H., 1980b, The Real-Time Animation of Three-Dimensional Maps, *The American Cartographer*, 7(1), 67-75.

Monmonier, M., 1989a, Geographic Brushing: Enhancing Exploratory Analysis of the Scatterplot Matrix, *Geographical Analysis*, 21(1), 81-84.

Monmonier, M., 1989b, Graphic scripts for the sequenced visualization of geographic data, *GIS/LIS 89*, 26-30.

Monmonier, M., 1990a, Strategies for the Interactive Exploration of Geographic Correlation, *Proceedings of the 4th International Symposium on Spatial Data Handling*, Zurich, Switzerland: Vol. 1, 512-521.

Monmonier, M., 1990b, Strategies for the Visualization of Geographic Time-Series Data, *Cartographica*, 27(1), 30-45.

Monmonier, M., 1992, Authoring Graphic Scripts: Experiences and Priciples, *Cartography and Geographic Informatin Systems*, 19(4), 247-260, 272.

Muehrcke, P., 1980, Maps in Geography, *Cartographica*, 18(2), 1-41.

O'Kelly, M.E., 1994, Spatial analysis and GIS, In S. Fotheringham & P. Rogerson (Eds.), *Spatial Analysis and GIS*, 65-79, London: Taylor & Francis.

Openshaw, S., 1994, Two exploratory space-time-attribute pattern analyses relevant to GIS, In S. Fotheringham & P. Rogerson (Eds.), *Spatial Analysis and GIS*, 83-104, London: Taylor & Francis.

Openshaw, S., Charlton, M., Wymer, C., and Craft, A., 1987, A Mark 1 Geographical Analysis Machine for the automated analysis of point data sets, *International Journal of Geographical Information Systems*, 1(4), 335-358.

Ornstein, R.E., 1973, Right and left thinking, *Psychology Today*, 6(12), 86-92.

Sandhu, J.S., 1990, *Combining Exploratory Data Analysis and Scientific Visualization in the Study of Very Large, Space-Time Data*, Ph.D. Dissertation, The Ohio State University.

Slocum, T.A., Robeson, S.H., and Egbert, S.L., 1990, Traditional Versus Sequenced Choropleth Maps/An Experimental Investigation, *Cartographica*, 27(1), 67-88.

Soffen, G.A., 1990, NASA's Mission to Planet Earth, *NASA Tech Briefs*, 14(1), 12-13, 81.

Thrower, N.J.W., 1959, Animated Cartography, *The Professional Geographer*, 11(6), 9-12.

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

Tobler, W.R., 1994, *Cholera: a BASIC program showing the Dr. Snow's map and Thiessen polygon boundaries around the pump*, In Santa Barbara, CA: National Center for Geographic Information and Analysis.

Tufte, E.R., 1983, *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, Connecticut.

Tufte, E.R., 1990, *Envisioning Information*, Cheshire, Connecticut: Graphics Press.

Tukey, J.W., 1977, *Exploratory Data Analysis*, Reading, MA: Addison-Wesley.

Tukey, J.W., 1980, We Need Both Exploratory and Confirmatory, *The American Statistician*, 34(1), 23-25.

Walker, P.A. and Moore, D.M., 1988, SIMPLE; An inductive modelling and mapping tool for spatially-oriented data, *International Journal of Geographical Information Systems*, 2(4), 347-363.

Wills, G., Bradley, R., Haslett, J., and Unwin, A., 1990, Statistical Exploration of Spatial Data, *Proceedings of the 4th International Symposium on Spatial Data Handling*, Zurich, Switzerland: Vol. 1, 491-500.

Young, F.W., Kent, D.P., and Kuhfeld, W.F., 1988, Dynamic Graphics for Exploring Multivariate Data, In W. S. Cleveland & M. E. McGill (Eds.), *Dynamic Graphics for Statistics*, 391-424, Belmont: Wadsworth Inc.