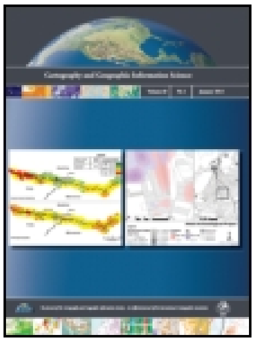

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Representation and its Relationship with Cartographic Visualization

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ABSTRACT: A research agenda is presented which addresses the current role and potential of map displays. By considering the geospatial data used in visualization, the form and design of maps, the purposes for which map displays are created, the nature of the map user community, and the technology employed to visualize geospatial data, a thorough overview of the nature of cartographic visualization is given. Under the same themes, and sourced in cartographic tradition, cartographic practice and technological opportunities, a series of possible research avenues are highlighted. The important links between representation and the user interface, map user cognition and the geospatial database are stressed.

KEYWORDS: Visualization, cartographic representation, map use, map user interaction, cartographic semantics, map display technologies

Introduction

Graphical presentation of information has a long history, and some of the earliest extant graphical presentations were maps. Cartography has had, and continues to have, an important role to play in the graphical presentation of geospatial information, such as that concerning the Earth, its people and environment, and other more abstract information for which geographic location is an important component. Graphical information representation and handling methods, including those defined as 'cartographic', are changing. As cartography's role and applications widen (in itself a development worthy of significant attention), we suggest that a) there are new things to represent; b) there are new methods of representation; and c) there is a need for an understanding of these—a new semiotics of cartography. The extended role of the map leads to new challenges for cartography, including further research into representation.

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This paper develops a research agenda addressing concerns relevant to such views. After a general introduction, a number of *themes*, including technology, geospatial data, and map use/users, are related to representation in order to prepare for further discussion on the current *state of the art*. This section examines the nature of contemporary cartographic representation, the variation in data that can be represented, and the tasks to which representations are applied. *Research challenges* are then detailed, each related to our assessment of the way in which cartography and its representation types and methods can progress. A *summary* confirms five broad themes that help to structure the paper and which together delineate the fertile ground for research in the area of cartographic representation: the nature of what kind of **data** and phenomena are to be represented; the **form** of representation chosen (e.g., conceptual model, database "representation," perceptual artifact); the **purpose** for which representation is undertaken and used: the **users** for (or by) whom representation is undertaken: and the methods and the **technologies** that enable representation to be accomplished.

Information Modeling

A viable data model of the real world that encapsulates the essence of the phenomena under study is a pre-requisite for the efficient management, use, and communication of geospatial information. Modeling of geospatial data is undertaken to ensure that data are captured, held, managed, and manipulated in a suitable way for applications covering (amongst others) archival, communication, or analytical purposes. In order to handle and view this information, a suitable means of transforming it into recognizable graphical entities is required. Modeling techniques are developing rapidly; but we need to further advance ways of transforming information about the world into models suited to digital and cartographic representations that lead to effective visualization. Such models should ensure fitness for use; should draw on research into the cognitive issues that surround increasingly personalized and flexible possibilities for map use with an expanded range of map forms; should respond to the state of the art in the realm of interfaces; and should drive (and respond to) developments in the field of databases and geocomputation.

Defining Representation and Methods of Representation

It is possible to regard modeling itself as a form of representation, but for this discussion it is assumed to be the data-handling step prior to subsequent representation. Cartographic representation is regarded here as the transformation that takes place when information is depicted in a way that can be perceived, encouraging the senses to exploit the geospatial structure of the portrayal as it is interpreted. Such representation encompasses the totality of the [Cartography]^3 structure developed by MacEachren (1994)—thus, all mappings of geospatial information into perceptible forms. The emphasis of the agenda put forward in this paper, however, is on the part of the cube labeled "visualization." The representations discussed are, therefore, primarily visual; tailored to specific users rather than for an unspecified "public;" intended for exploring unknowns; and highly interactive (possessing possibilities for manipulation by the viewer). Such representations differ substantially from conventional maps, and there is a need to research these new methods of geospatial information exploration and presentation.

Themes and Issues

Issues in Representing Geospatial Data

Associated with geospatial information representation and exploration are issues related to the nature of the underlying geospatial data—their differing types (e.g., multivariate, spatio-temporal, uncertain); their differing properties (e.g., scale, meaning); and their differing methods of collection and storage (e.g., satellite remote sensing, mail survey, field GPS). We may require different representations for different data. For example, the use of Levels of Detail (LOD) as a cartographic concept similar to generalization is now accepted (Reddy et al. 1999). Progressive meshes for landscape representation (Hoppe 1997); variable resolution ("pyramid-layered") bitmaps for image representation (Pavlidis 1982); methods of combining surfaces and images for rapid representation in an interactive environment (including novel data compression techniques such as wavelets) (Muchaxo et al 1999); and techniques for streaming geospatial data across a network so that representations can change seamlessly as and when required (Schroeder et al. 1997), all take advantage of particular data structures. Sonic data, time-dependent data, and dynamic and animated data also each require special consideration and an examination of optimal methods for incorporating them into representations for visualization. It is necessary, as well, to consider the portrayal of some of the inherent characteristics of data, notably their quality or uncertainty. We are now able to explicitly include these elements within representations used for knowledge acquisition and decision-making.

The types of phenomena that are being recorded, the data that are being collected, and the mechanisms used for their storage, are changing. The models upon which many maps have traditionally been based are also changing. Automated collection techniques allow us to represent additional phenomena in new ways: the masses of data now being compiled are ripe for representation using cartographic techniques and for investigation with visualization. But how do we store such data in order that we can manage them efficiently, portray them effectively, interactively visualize them, re-configure, re-express them, and combine them with other sources, and, what are the best methods for representing them cartographically?

We cannot consider a representation method for the data until we comprehend the phenomenon fully. The establishment of formal metadata standards is a step toward establishing links between data and phenomena, but more comprehensive approaches to semantic frameworks for managing the meaning associated with geospatial information are needed.

The Form of Representation and the Impact of Semiotics

The publication of Robinson's seminal work *The Look of Maps* in 1952 stimulated wide-ranging, scientific research into the effectiveness and aesthetics of cartographic design. Such research suggested that an understanding of the "language of representation" and its effect on the look of maps was necessary. Much of the subsequent work developed by Bertin (1967), Mackinlay (1986), and Cleveland (1993) for graphics, and extended by Krygier (1994) for sound, and by MacEachren (1995) for time dependence, addressed the "variables" or "building blocks" of such language and their associated semiotics. In many cases, the new media and tools that cartography is utilizing, for example virtual reality (VR) and multimedia, possess semiotic relationships that can be and are different to those traditionally applicable in conventional map display. Cartographic representations are ever more variable, they can use differing components and methods, and the impact of data modeling and the effect on those utilizing the maps, can vary considerably. The visualization of geospatial data in its widest sense, therefore, involves issues of what form representations take and how they are used.

Contemporary representations often display "non-conventional graphics" that are different from traditional static, two-dimensional mapping. A whole range of map behaviors are possible in the evolving world of dynamic mapping where the previous practice of representing both static and dynamic information by unchanging symbolism on paper has been replaced by temporally varying displays for both types of information on screen. This situation is potentially confusing, requiring analysis of the types and roles of dynamic display that are appropriate for visualization so that "good practice" can be identified and formalized.

Shepherd (1995) notes that temporal variation can arise from several sources including the data (e.g., using temporal symbolism to portray data characteristics); the software; the observer (e.g., changing representations with a viewer's developing train of thought); agents (e.g., symbolizing agent behavior for analytical purposes); the intrinsic relationship between map elements (e.g., entity-related behaviors can be used to change map elements when certain relationships occur between them); and the designer (arbitrary behaviors can be introduced by the designer to add cosmetic interest or dynamic embellishment). Classifying distinct map behaviors provides a framework upon which research can develop new methods of representation that are effective and efficient.

Representation and the Purpose of Mapping

Cartographers continue to address the role of map-based representations for a wide range of tasks and in differing contexts, many of which are relevant to, and have been addressed from different perspectives by, researchers in other fields. When using visualization methods, whatever the task or context, the mode of representation should be under user control and a classification of representation methods and their potential application areas should be readily available to those exploring geospatial data. Associated with the application of an appropriate representation method, it is important to ensure that the appropriate level of data abstraction for that representation is displayed. Further, it is critical that, once displayed, we are also able to navigate and effectively assimilate all of the data that are available to us using interactive graphical tools.

Some problem solving would benefit from the establishment of formal links between visual and statistical analysis, and between hypothesis generation and hypothesis checking (Gahegan et al. 2000). These links have the potential to result in visualization methods that produce added value in scientific research, thus moving visualization away from an exercise that merely gives rise to wonder and/or uncritical speculation, towards a role that achieves new insights and supports critical inquiry.

Such insights are, of course, very much under the control of the user. The major difference between traditional methods of geospatial data representation and our goal of insightful visualization, supported by future methods of representation, is the potential to enable a proactive role for the user (Buttenfield 1993). This is exemplified in the possibilities of choosing, changing, and interacting with representations as diverse as "worlds" created and coded using the Virtual Reality Modeling Language (VRML), graphics derived from exploratory data analysis (EDA), and avatar-based "theatre stages." Although direct user manipulation is possible there are circumstances where interaction with geospatial data may be undertaken by novices or in a tentative manner; automated techniques of data mining may be implemented here to aid exploration and analysis. In addition, knowledge discovery techniques, decision-making strategies and artificial intelligence can aid, somewhat more interactively, initial choices and subsequent manipulation of appropriate representations; these methods seem likely to provoke renewed interest in visualization.

The ability to perform multi-scale analysis is critical for an increasing array of business and scientific problems. Current visualization tools seem to support one scale at a time, or at best allow us to move from one scale to another without any real support for investigating how patterns and processes at one scale relate to those at others. Cartographers have solutions to offer to this difficult problem. Cartographic practice relies on the abstraction of geospatial data, its graphical representation and the subsequent design of map-based products. These are presented at differing scales and levels of detail; cartographers have significant expertise in handling geospatial data at multiple scales and for varying purposes. The experience of addressing problems of map generalization provides methods through which cartographers can efficiently create multi-scale representations of spatial data in various forms.

Representation and Map Users

A further issue in considering representation is the user community itself. As interaction is such an important component of representations for visualization and virtual environments, study of the impact of new media displays, interaction of users with them, and the reaction of users to them will be helpful in determining appropriate representations. We also need to examine the effects of developing techniques for portraying geospatial information, such as positioned sound and truly three-dimensional methods of projection. How such methods can be combined and how they relate to multi-user modes of interaction are also important, as is the role of traditional map elements such as symbols, legends and scales. In addition, we should be able to sense feedback and the interactivity involved.

The interaction of users with animated displays deserves specific attention, as it is of relevance also to issues of data for, form of, and use of representation. To support creative exploration of highly multivariate spatio-temporal information, we need to move well beyond the video-player metaphor for interacting with animations. In addition, the role of dynamism in VR and its impact on the viewer is worthy of further investigation. The effect of multi-user environments is also of considerable contemporary interest. An important issue here is to develop approaches for matching new representation forms to tasks and use contexts. In considering the users of cartographic representation, it is necessary (and standard practice) to recognize different competencies of users, distinguishing between novice, or casual, users and experts. Adaptive representations are needed that take account of these differences.

A result of the attention given to this issue by a range of researchers (typified by other contributors to this volume) should be a paradigm for understanding the cognitive implications of new representation forms, for assessing their usability, and for developing guidelines to match representation forms with tasks and contexts. A specific representational goal is to extend past efforts to automate the mapping from data to display.

Technologies and Representation

As a range of technologies is being applied to visualization, it is important to have knowledge of the developments on which many new cartographic media rely. We are now able to represent data dynamically, or with sound, or over the Web, or using mobile communications (such as with the wireless applications protocol, WAP), or within a virtual environment, or attached to a wider GIS database, or in ways that allow abstract representations to be superimposed on our view of the real world (through augmented reality using head-mounted displays). From a practical viewpoint, it is necessary to determine the scenarios in which these representation methods and forms are a valuable addition to visualization, and subsequently how we best incorporate them.

As the critical issue is to ensure that the method matches the task and the data, technology needs to be effectively utilized in multimedia environments where the linkages between displays of the same data in different forms have to be established and active. Similarly, we will employ technological means to combine different datasets (e.g., terrain data, sound data and navigational and gravity sensors) in the same display device.

The themes and issues detailed above in five sections identify aspects of the relationship between representation and visualization that are changing and require a research response. To re-iterate, we consider the most critical issues to be those concerned with the characteristics of the **data** to be handled (including issues of its generalization, organization and its inherent attributes); the appearance and **form** of representation (visual design and the user interface); representation **purpose** (including matching the representation with generic or specific data handling tasks); the impact of representation form on both understanding and task outcomes (in particular, user interaction with dynamic representations and with other **users**); and the changing **technology** to support new forms of representation.

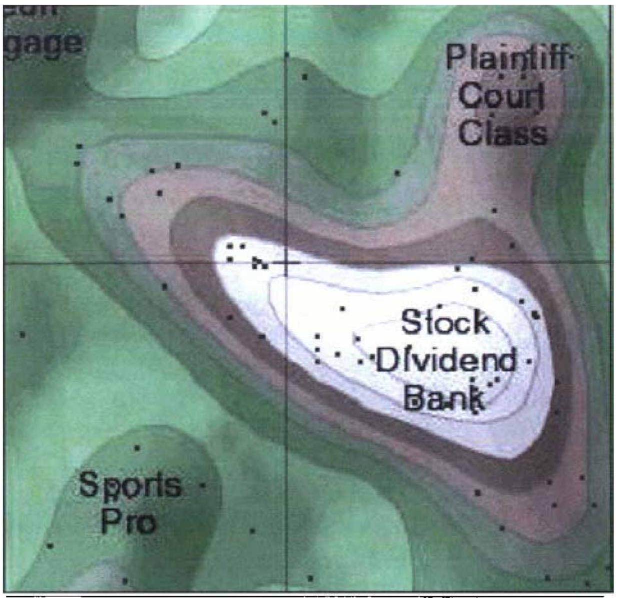


Figure 1. Themescape example.

State of the Art

Recent work in the discipline of cartography has expanded the range of representational methods. These new forms of representation all possess elements that characterize cartographic visualization (interactivity, investigation of unknowns, private study). The implications of this expanded cartographic 'toolbox' are closely related to the other issues addressed in this volume - interface design, cognitive research and other methodologies such as data mining, geocomputation and GIS, demonstrating the need for close communication between those with a whole range of skills and interests in visualization research, and a structured approach from the community as a whole.

Role of Cartography and the Map

Representation is intimately connected with interaction, visualization and the human-computer interface. In aiming to identify a coherent and comprehensive research agenda for the community, we address these relationships by examining a wide range of forms of representation, of both well-known and less familiar phenomena, and examine a variety of possible methods of representation, not merely visual methods. We do so within the paradigm of a general cartographic modeling theory that describes the influences of abstraction and design on the one hand and the influence of individuals (as users) on the other.

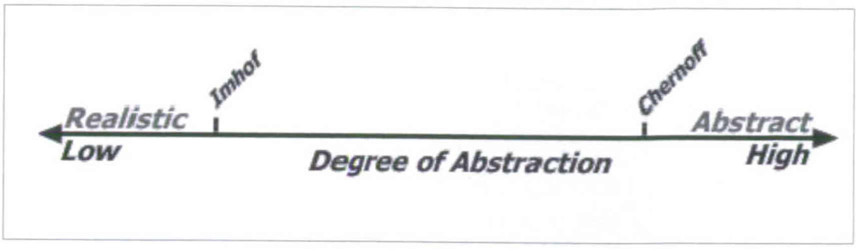
Conceptual research into map production and use over the past decade (DiBiase 1990; MacEachren 1995) has concentrated on how map-based displays can enable creative thinking and problem solving in scientific and geographical enquiry. By distilling and portraying geospatial data, cartography has a central role to play in such information handling. It allows us to portray raw data, the graphical combination of disparate data sets, the graphics-led probing and exploration of data and the presentation of results. As a combination of abstraction and representation, cartography is a data-handling and data-communicating method *par excellence*. The primary representation of cartography—the map—forms a powerful and extremely popular metaphor for the exploration, extraction and summary of all types of data, not merely geospatial data. Most of the techniques used in contemporary scientific visualization have relied on mapping methods to provide their initial model (Collins 1993).

The Map as a Representation and Other Metaphors

The map is often seen, therefore, as a metaphor for the presentation and representation of all types of data, spatial and non-spatial. Other metaphors exist by which geospatial data handling can be characterized (Cartwright 1997); some of these are narrative (The Guide, The Sage), others are more numerical (The Factbook, The Toolbox). While these metaphors provide important supplements, the map metaphor is central to cartographic visualization and pervasive within scientific and information visualization. It supports the representation and exploration of a wide variety of complex information that can be mapped to display "space." Today, data and information that have traditionally been described, enumerated, tabulated, and summarized are being mapped.

An example of how the map metaphor is being applied beyond cartography is ThemeScape—implemented in software entitled SPIRE (Wise et al. 1995)—a technique that illustrates the density and strength of relationships among non-spatial data, such as stories in the on-line press (Figure 1), using terrain-like plotting methods. Also in the virtual world, the visualization and understanding of web connections in cyberspace has benefited from use of mapping tools (Dodge 1999). Even in geospatial data handling, features such as topographic slope, aspect and surface artifacts (borrowed from the physical landscape map metaphor) can be used in the mapping of other types of geospatial data such as socio-economic variables (Wood et al. 1999). The map metaphor is potentially broad in its derivation and application. It covers representations that can vary considerably in their degree of

Figure 2. Continuum of realism with Imhof and Chernoff representations (Dykes et al. 1999).



abstraction. From a cartographic perspective, at the lowest degree of abstraction, equivalent to the "realistic" end of a continuum, are terrain renderings such as those of Imhof (1982). At the other end of the continuum are "schematic" views such as those of Chernhoff, whose facial representations using parameters of eyes, nose, mouth, and ears can be used symbolically as individual map elements (Dorling 1994). Both of these representations transform the data to take advantage of the methods of cartographic representation that we have available, our cognitive and perceptual skills and our experience in interacting with reality to represent geospatial data in ways that allow us to interpret them effectively. The level of abstraction required to successfully achieve this varies: Imhof applies subtle local variations in lighting angles to accentuate relief; Dorling's maps of Chernhoff faces necessitate more abstract transformation (Dykes et al. 1999) (Figure 2). Further extremes of the continuum occupied by 'non-cartographic' representations such as diagrams, graphs, pictures and photographs, also use abstraction to aid efficient interpretation of reality

Developments of the Map Metaphor

The continuum of representations is constantly expanding, thus the map metaphor (traditionally derived from our understanding of static paper maps) is also evolving. The general development of virtual environments, and the incorporation of cartographic effort into their exposition, has led to an expectation of evermore-realistic cartographic representations. This is enhanced by current software, including three-dimensional computer graphics toolboxes such as UNIRAS, AVS (Rhyne 1994), IBM Data Explorer (Treinish 1995), VisAD (Hibbard 1998) and NAG Explorer (Wood et al. 1997) and graphic specifications, such as VRML, which interface to such representation building toolboxes. Like a traditional map, however, such representations are still based on abstraction and design. Whether the representation used in a virtual environment is realistic or abstract, the interpretive load put on the user may be minimized by providing realistic interaction with the representation. Even if realism is an objective of the representation, and the representation and forms of interaction are realistic, the experience with "reality" is indirect (relying upon the cartographic transformations implicit in the representation). Research into the creation, specification, use, and assessment of such modern maps will rely upon many developing aspects of cartography.

Buziek (2000) lists further aspects that affect map representations and the user's response; these can be profitably examined to determine factors to be borne in mind when constructing representations and considering their use. We have already specified *level of interaction* as active in characterizing geographical visualization (or "geovisualization"), although, clearly, for most traditional representations it is passive. Dependent on the data modeling process, representations can portray 2, 2.5 or 3 *dimensions*. The *dynamism* of representations is a further parameter, ranging from static to moving or animated displays. The *sensory channels* used to access the representation can vary, including visual, acoustic and haptic methods. The user can also access the representation from within differing *environments*, for example immersively, or remotely. Connected to this, the *media* through which the representation is conveyed can vary—for example, using paper, screen, projective display (as with augmented reality) or computer assisted virtual environments (CAVEs). Some of these environments and media allow for multi-*user access*.

Clearly, a number of enhancements to the map representation can be brought to the study of the map as a metaphor for accessing geospatial data. The development of the map as an artifact parallels the development of spatial data characteristics, thus ensuring that the traditional iconic role of the 2D, static, visually perceived map representing a visually perceived, two-dimensional, static landscape is changing. As the nature of the geospatial data we are handling changes, so the map representations, which are used to visualize it, change also.

The ability to display non-spatial data in a spatial way, and to similarly represent spatial data using inherently non-spatial displays, is offered in techniques embedded in current visualization software tools. Multi-dimensional scaling, for example, is possible using XGobi (Swayne et al. 1997). Hovmuller plots, which combine spatial and temporal dimensions in one graphic, are used in some geophysical applications (Harris et al. 1996). Dorling (1994) produced representations that transform space and time with his algorithm for cartogram projections. Parallel coordinates plots can be dynamically linked to maps and cartograms and cartographically symbolized to show structures in attribute and geographic space using cdv (Dykes 1998). Descartes also supports such multivariate representations of spatial and non-spatial data using similar dynamically linked constructs (Andrienko and Andrienko, forthcoming). The Exploratory Data Visualizer (EDV) can use Nicheworks, a tool for exploring large graphs where there are many variables on both nodes and links (Wills 1999). These are of particular interest to those exploring spatio-temporal interactions where the representation of, for example, one spatial dimension using animation could "release" that dimension for the portrayal of time-dependent data (Edsall et al. 2000). "Projection pursuit" is an example of such techniques applied to high-dimensional data (Friedman 1987). In general, contemporary visualization opens opportunities to escape from iconic displays to more abstract representations in which space can be wrapped into non-spatial elements of display.

All these aspects, related to the development of the map, can extend our overview of representation methods beyond the continuum described above (that summarizes graphical appearance from realistic to schematic). Consideration of technology and interface design further extends the scope of representation method: technology enables new representations and new representational demands prompt technological advances. The introduction of dynamism, animation, interactivity and hyperlinking has led to new methods of display. Research is required in order to ensure that these are appropriate and useful, that the data models that underlie them are enabling and suited to visualization rather than restrictive, and to assess their impact.

In addition to technology and the user, we should note that representations can be affected by externalities and data properties (e.g., the nature of data reveals an intrinsic dimensionality, the contents of the data have an effect on the sensory channels that can be used, the meaning of the data has an effect on user task). A recognized cartographic principle is that representation is data- and task-dependent.

Schematic and Realistic Representations

Exploratory data analysis (EDA) techniques rooted in statistical data handling (Tukey 1977) allow for representations that are generally schematic, yet still of interest to cartographers. Developed initially to assist in automated data mining and interactive data exploration, there is considerable potential in using techniques such as brushing and focusing (Carr et al. 1987), for representing multivariate datasets. Extensions, such as "strumming," an interaction method for use with parallel coordinate plots that are dynamically linked to maps, have been proposed (Edsall 1999). The contemporary results of such work include accessible software such as cdv (Dykes 1998), Descartes (Andrienko and Andrienko 1999a) and GeoVISTA *Studio* (Gahegan et al. 2000).

A substantial research effort has also been directed towards the realistic representation of physical phenomena, rather than the more schematic representations mentioned above. In creating such representations of the "real world," researchers have used geovisualization along with knowledge of how human beings interact with and view their environment. In addition, these representations can make use of all human senses, including audio and haptic interactions as well as visual contact with a representation.

Both technical and conceptual work is needed to extend and fully explore the range, consequences, and suitability of these new, dynamic representations of geospatial data.

Task-driven Representations

The representation of scientific hypotheses (e.g., in sketch form), of scientific data (e.g., in archiving and for communication purposes) and of scientific results (e.g., in pictorial or graphical summary) is undertaken for many tasks. The exploration of complete scientific datasets requires different representations of the comparison of a pair of individual observations. The summarizing of a complete scientific investigation is rendered in a different form than the highlighting of a dataset outlier. Summarizing, exploring, extracting, and the identification, comparison, and interpretation of features are all scientific tasks that can lead to varying types of representation.

Technological Possibilities

The map metaphor is well embedded in the mindset of the majority of the public, and also of dedicated scientific researchers. New representations that have developed from these roots are less familiar. The possibilities afforded by contemporary technology, along with interaction of users with the subsequent representations and the linkages with wider scientific endeavor, will broaden the scope of cartography in user communities. Cartographically familiar tools and parameters (e.g., color) need to be reassessed in light of these changes. Application areas for new cartographic media are constantly widening: witness the role of mapping in corporate business, the financial and insurance sectors, Internet mapping, and contemporary geo-location devices. As the realm of human endeavor to which geospatial data can contribute expands, the range of methods of portrayal widens and the need to develop and test the most appropriate techniques continues.

Research Challenges

The major research challenges that we identify in the visualization of geospatial data each involve rationalizing the wide range of factors affecting and affected by contemporary and future methods of representation. We feel that the cartographic community, working with others, can (and should) play a leading role in the search for solutions to these tasks. In this section, we delineate challenges and set forward aims related to the five aspects of representation we have stressed already:

- To fully appreciate how representation is affected by geospatial **data**;
- To address conceptual issues in creating representations and to formalize a theory of the **form** of representation;
- To know the possibilities, applications, and limitations in the tasks and **purpose** of representation;
- To comprehend the interaction that is involved in accessing representations and the impact of the **user**; and
- To be familiar with the tools and **technology** that are used in representation.

The Impact of Data on Representation

This section considers some research tasks in the area of the geospatial data used to create representations, the inherent meaning of those data and linking such meaning to the form of representation, and the impact of data attributes on the representation method.

- Firstly we need to address issues related to the *size* of the dataset. Visualization of very large (terabyte and bigger) data sets has been identified, previously, as a critical research issue (e.g., in the NSF Program Announcement 99-105 on Large Scientific and Software Dataset Visualization). Most of the very large data sets being considered have geospatial components (e.g., those from the Earth Observing System, telecommunications records, national census and health databases, or from environmental process models). The challenge related to geospatial data representation is to move from representation methods developed in an era of data scarcity to new methods that deal with data glut.
- A common characteristic of contemporary data is their dynamic nature. Clearly, animated and vibrant forms of representation can be used to address the problems of integrating time-dependent data into geovisualization systems. Such dynamic display may provide part of the answer when tackling a geovisualization challenge critical to applications in environmental science, transportation engineering, and other domains in which changes in both space and time are relevant—the challenge of *representing process*. The problem is not how to represent "temporal data" but how to represent "processes occurring over time." We believe that a focus on representing temporal data has limited thinking about how process might be represented; it seems to constrain representations to displays such as snapshot views typical in GIS databases, if they include time at all. The possibilities of detecting and evaluating changes, showing states at particular moments, displaying trends and assessing time dependency (are phenomena permanent, transient, periodic, renewable? do they split, merge, spread, move?), all need closer scrutiny.
- A *representation of uncertainty* may supplement existing data or may be an item of display in its own right. Making information available about data uncertainty, stored metadata parameters and/or the suitability of a representation for a particular task is essential, if users are to make informed decisions and we are to extend the visualization toolkit. A comprehensive program of research is needed to ensure the development and test (in a variety of circumstances) the efficiency of quality or uncertainty indicators for new methods of representation.
- There is clearly a wide range of further exogenous information, both qualitative and quantitative, which can be (and often needs to be) assimilated into the analysis of geospatial data and its representation. Mechanisms such as XML can be used to formalize this and assist in the addition of more *contextual information* to our representations.

- Choosing a method of representation that is appropriate to the task and data to be portrayed is crucial. To this end, our investigations should move beyond the consideration of variables of representation—and associated syntactics or rules for matching them to data types (which are important)—to an examination of the *semantics within the data*. Full comprehension of the nature of the data and phenomena to be mapped is necessary before representation can be undertaken. Recently created visualization software has offered intelligent graphical representation of data using metadata and a cartographic rule base (e.g., Vizard (Jung 1995); and Descartes (Andrienko and Andrienko 1999b)), but such extensions into interactive display have revealed the shortcomings of previous expert system tools. Understanding the role of map displays in visual thinking and the tasks involved in using maps for exploratory analysis may lead to a new assessment of the potential of expert systems in contemporary displays.

Forms of Representation and Representation Theory

As we extend the definition of cartographic representations we need to address the limitations of traditional cartographic methods along with the possibilities of new representation methods and the nature of their implementation.

- Research is needed into the fundamental *representational primitives* that can be combined to support creative visualization. Visual, sound, dynamic and tactile variables have been discussed already, but an assessment must be made of the relative strengths and effectiveness of each, how they are isolated as variables in their own right, and when they might be suitable to apply. In addition, a theory-based approach to the combining variables for complex multi-dimensional visualization is needed. The impact of technology on newer possibilities in representation (e.g., the use of dynamic symbols that vary rhythmically) also needs investigation.
- It is important to determine the nature of *animation* as a tool for exploratory analysis, beyond its straightforward display function. Shepherd (1995, p. 184) suggested that "whenever dynamic features are added to maps [we should] ask the question WHY?" Attention should also be directed to HOW? and WHEN? dynamic graphics can be used appropriately and successfully for visualization.

  As cartographers engaged in experimenting with animations we know that there are problems in viewing these "as a whole" (Morrison et al. 2000). Whilst we have managed to develop more exciting, impressive, busier, faster graphics, we have not advanced our knowledge of dynamic representation. By addressing map behaviors and considering the distinct roles played by temporal variations in map display, different representational possibilities, user experience and preferences, and the task at hand, we may identify conflicts and begin to address the fundamental issues.

  In the most successful displays, the speed of animation can be controlled to examine possible periodicities in the data, different starting points can be chosen for simultaneous displays, and pattern analyzers can be employed. The ultimate aim is for what we term "analytical animation," whereby interactive tools for exploration and controls for playing through multiple scenes are combined, allowing for efficient data extraction and understanding. One approach to the implementation of analytical animation is to take advantage of advances in video techniques (e.g., coding in MPEG-7 format). Extracting information from video and exploiting interactive video, however, requires new data models and interfaces and novel graphical representations.
- The application of *non-conventional graphics* for representation covers a range of techniques that require study. The use of superimposition (such as overlapping and integrating graphics with simultaneously sensed reality or imagery); multiple viewpoints (simultaneously displaying three dimensional phenomena from a number of viewing positions); morphing and animation (to help in portraying change); and highly schematic or highly realistic representations (dependent on the data, the user, and the task involved) call for fundamental research enquiry to determine their effectiveness as standard tools for geovisualization.
- The specific issue of the desirable *level of realism* in cartographic representations is of immediate importance as geospatial data (especially image data) become available at ever-higher levels of resolution and as the complementary need to abstract a simplified representation from complex data becomes apparent. The increasing use of VR raises questions regarding human interaction with the spatial representation. There is a potential difficulty in rendering VR scenes as "more real than real." The

extraction of graphical data from the imagery of an aerial photograph, for example, can yield a more useful product—the map—than the original. Similarly, a more generalized display may be more effective for interpretive purposes than a highly detailed and complex virtual world. As we increasingly utilize technology that can merge the abstraction rendered by cartographers with the realism presented by contemporary computer graphics techniques (e.g., in games technology), we need to determine the relative levels of each for the task in hand.

- *Sound* is seldom considered as a fundamental component of visualization, generally limited to use in enhancing realism of virtual environments via natural sounds. Its potential as a complement to vision for representing complex geospatial information is virtually unexplored. Sound, like vision, is multivariate and capable of being spatialized, for example, in VRML and Java 3D where a coordinate position, range and direction can be specified. Whilst initial tests suggest some success in using sound to extract patterns from multivariate data there are further critical areas of concern which are integral to the incorporation of sound within visualization. These are the sound variables and their inter-relationships; the link between sound and time; the use of sound as a spatial location mechanism; the reaction of users to sounds ("psycho-acoustics"); the role of conceptual and realistic sounds; and the incorporation of the human voice in geospatial information systems.
- We should consider also the potential of *haptic* (touch) *techniques* as supplementary representation forms (Yokokohji et al. 1996). Haptic communication of spatial variables and environmental aspects are areas yet to be researched in depth, and it is clear that such methods are used more for interacting with spatial data rather than representing them. Technology already exists to portray resistance in a tactile manner—which could be used to represent attractiveness, gravity models, or theoretical location-planning scenarios (e.g., feeling the competing pressures for facility siting)—but whether further tactile variables such as temperature, texture/roughness or humidity can be effectively used to represent geographic information is less clear.
- Possible mechanisms for transferring data, edits, and information between representations have not been explored thoroughly. We have established that distinct methods of representation exist on our continuum shown in Figure 2. There may well be multiple solutions to the problem of how to efficiently represent a specific data set such that differing views of the same data (varying, for example, in scale, level of realism, dimensionality, dynamism) can be created. Data handling and analysis may be improved further by establishing relationships between such *separate representations*. It is technically possible, using existing standards and tools such as HTML and Java, to ensure the propagation of changes through different and separate representation methods. For example, a simulated landslip in a realistic terrain-viewing package could dynamically alter the contour pattern on a two-dimensional topographic map of the same area, rendered in a separate window. Such relationships can rely on object-based computing technologies that embed behavior into objects rather than into representations. Currently, although multiple representations of geospatial information are becoming standard, these tend to be loosely coupled data streams, which may refer to the same information content but are not capable of dynamically linking the representations. The graphical tools of EDA, such as "brushing," do allow user interaction to have simultaneous impact on linked objects/places in multiple views, although human understanding of the linkages displayed may be limited. Even existing issues such as the impact on the viewer of varying representations of the same landscape or feature from *multiple viewpoints* have not been sufficiently examined.
- Deriving meaning from geospatial data often requires complex data processing operations that data users may not understand, resulting in misinterpretation of data and subsequent bad decisions. The *visualization of geospatial data processing* operations can ease their interpretation and support effective and appropriate data application. One approach is to extend visual programming metaphors of the sort found in AVS, IBM Data Explorer, and GeoVISTA *Studio*, and standard geospatial data handling packages such as ERDAS Imagine. Such visual methods can be further applied to processes of data querying and analysis. Our experience with these visual programming techniques indicates that the relationship between them and visualization requires further investigation.

Tasks and Applications—the Purposes of Representation

The fundamental question behind this challenge is, "What is a suitable method of representation for this particular task?" This question is particularly difficult to examine, relying as it does on un-quantifiable factors such as an assessment of knowledge acquisition and the efficiency of data exploration. It can be hard to answer the question of whether insight results from the individual expertise of the user or the effective rendering and use of visualization. Cartographic and graphical representations, including those offered by EDA, can assist significantly in providing a framework for exploring this area: the Descartes mapping tool, for example, can act as the geospatial data display extension to the knowledge discovery package, Kepler (Andrienko and Andrienko 1999c).

- The use of graphical editing tools in practical visualization tasks can be supplemented by integrating the type of statistical tools used in EDA and data mining. The creation of animated and multi-media visualizations as a result of data mining has not been fully explored. Further, there is a need to develop *graphical data mining techniques* for the initial exploration of spatial representations.
- The effectiveness of representation is inextricably linked with the behavior of the user in interacting with the display; we need to determine the purposes of using visualization – for summarizing, exploring, extracting etc. Basic research questions therefore might include 'What is the relationship between *knowledge discovery* and representations?' 'Do representations change how decisions are arrived at?' 'At what stages in knowledge discovery can visualization be used?'
- It is expected that maps will prove to be of significant use in some geospatial *decision making* processes. We should note in particular the important potential role of visualization in integrating multivariate datasets and in facilitating the representations of environmental scenarios, problems, and solutions. DiBiase et al. (1994) suggest that users prefer univariate small multiples, rather than single composite multivariate maps—but the relative advantages and disadvantages of each are still in question. Multi-criteria analysis could benefit considerably from such displays but clearly there is need to develop appropriate and task-specific representations. We feel that interactive representations show most promise in this particular geospatial decision-making process.
- Representations that incorporate dynamic, three-dimensional interfaces provide realistic display for a range of environmental and other workers. If such techniques are supplemented by augmented reality, whereby the real world can be seen through a superimposed image, perhaps with sound enhancement also, military personnel in training, fire-fighters and mining engineers could all benefit from representations, mainly of a schematic nature. Augmented displays allow users to cope with both the complexity of the real world and the integration of information that is difficult or impossible to sense whilst within that world. Further research is required to determine exactly what is required from these *superimposed portrayals*.

Users' Responses to Representations and Implications for Interactivity

A fundamental concern within the area of user studies and their responses to visualization is whether representations are being accessed in single or multi-user environments.

- Virtually all past work on visual representation has been directed to representations used by one individual at a time. A conceptual and practical approach is needed to develop *representation forms explicitly designed to be shared.* Multi-user environments are of importance for a variety of researchers and decision-makers who are engaged in group work. In practical terms, "virtual workbenches," as shown in Figure 3, might support mission critical handling of dynamic, three-dimensional spaces (e.g., in air traffic control) that requires the input and participation of a number of users. Such multi-user environments require study to determine apt methods of representation and interactivity.
- The efficiency of representation may be governed by user reaction to the data being portrayed. It may be possible for the same data, for example some terrain information, to be represented by a DTM mesh, a rendered perspective view, or a planimetric map. *User perception* may be directed by preference, experience and competence; appropriate representations for differing user communities are needed. The role of visualization by air traffic controllers is clearly of considerable importance, as is the representation of the route of a tourist hike for adventure holiday participants. These user groups are likely, however, to have differing experiences for using, expectations from

Figure 3. The Immersive Workbench and observer with stereoscopic glasses, tracking system and stylus (Ottoson 1999).

and interactions with, the representations presented.

- Facilitating *navigation* in complex representations of geoinformation spaces is a fundamental research challenge. Investigations into interactivity will clearly play a role in approaching this challenge, as will work on interfaces and user cognition. In terms of representation, there are issues such as displaying current position within the environment, routes previously followed, and possibilities for movement, which need addressing to ensure efficient navigation. Methods are already established to initiate "external interactivity" from within cartographic visualizations: access to web sites, linkages to external databases through brushing, and triggering of statistical analysis from within a representation are all possible. Further development is required to establish a more useful method, which we term "internal interactivity," whereby traditional map displays can be altered in response to user input; or to automatically determined analytical parameters. This might extend to finding new ways of identifying, selecting or concentrating on data within a map or even measuring user eye-movement parameters. Methods of doing this will incorporate research into intelligent agents and other automated tools, which allow for 'smartness' to be included within the map display.

Representation Tools and Technology

A range of display technology methods is already used for cartographic representation and embedded into visualization systems for handling geospatial data. There is considerable scope, however, to further research into the representation methods that take advantage of new technologies, such as those enabling new kinds of representation in sound or dynamism.

Hardware

- An increasingly important technology associated with spatial data handling is "wearable computers" (Mann 1997). In relation to the representation of geospatial data, these provide mechanisms whereby data can be presented to an outdoor user to supplement the real world ("augmented reality") or by which data can surround a user's senses within the confines of a head-mounted display (HMD). Questions remain regarding the interface between the artificial world as superimposed on a filter over the eyes and the real world viewed through it: what kinds of representation are appropriate for tasks where such constructs are used? What representations can be employed in HMDs to improve a user's experiences of reality? The term "wearable computers" can also cover distinctly different technologies such as *mobile communications*. In this context, an important research challenge is to develop new, perhaps multi-modal, representations that are effective on mobile communications devices with restricted graphical capabilities.
- *Immersive environments* have been further developed recently, initially with "video-walls," giving large-format representations of spatial environments, to fully enclosed CAVEs in which realistic images of spatial representation can engender natural and added-value responses to data. What is the role of abstract data representations in immersive environments and how is visualization best undertaken?

- In addition to design issues, the practical technology of *multi-user environments* is also of importance. These methods of display, which can also be immersive, allow for social interaction and shared experience. They can involve an assembly inside a CAVE; group viewing of visualization monitors; web-based multi-user interaction; and the use of avatars and other surrogates within a scene. Such interaction can occur simultaneously or separately in time and/or place, and is of considerable benefit during the course of co-operative problem solving and decision making in a geospatial context (e.g., in environmental management or in city planning). Do collaborative multi-user environments require different forms of representation and how do we achieve these in a visualization context? How can we represent complex, multivariate, multi-scale geospatial data to groups of users (who may bring different disciplinary perspectives or social concerns to the task) in ways that facilitate collaboration among individuals on tasks such as finding relevant information in vast data warehouses and making decisions based upon those data? How do we represent the existence, actions, relationships and viewpoints of each user in a group of collaborators most effectively?

Data Formats and Coding Methods

- *Software tools* for creating VR scenes (such as VRML, OpenGL and Java 3D) can form the basis for accessing new, possibly hyper-realistic, representations of spatial reality. Each of these tools shares a core goal of cross-platform compatibility—particularly important for supporting the extension of geovisualization methods and techniques (developed to facilitate scientific research) into an increasing array of new domains that includes business, education, planning and decision making applications. The existence of the GeoVRML working group is indicative of the potential role of co-operation between cartographers and the wider computer graphics community. The format and scope of VRML as a whole has been positively developed by this group (Reddy et al. 1999). These techniques allow for the enhanced and detailed representation of data projected into three-dimensional views of geographic space that respond at speed in real time. They act as natural interfaces to data beyond the two-dimensional static map.
- Research into the means of *rendering* such representations must address concepts that cartographers have addressed in previous conceptual research. The portrayal of text, the possibilities of color and shading and the techniques of legend creation are a few examples of standard cartographic concerns that take on a new urgency, in the context of evolving technologies for representation, interaction with representations and dissemination of those representations. These traditional, if expanded, concerns are matched in three-dimensional environments by questions such as: what is the nature of data best suited to such display; are design issues for immersive environments different to those of two-dimensional static maps; to what extent should levels of detail (LOD) be incorporated with representations; and how do we stream such data from the data model, through communication links to a realistic and data-rich representation?
- Novel web-initiated techniques for coding and structuring data, such as XML (eXtensible Markup Language), GML (the geographic XML implementation) and SMIL (Synchronized Multimedia Integration Language), will provide means for handling geospatial data (Bosak and Bray 1999). Ultimately "stylesheets" for visualization that encode knowledge about exploratory techniques for geospatial information might be developed and applied based upon the data, user, and task in hand. Transformation is fundamental to representation for visualization and the XSLT specification provides a means for transforming between different representations defined in XML.

Synthesis and Linkages

This volume addresses the work of the ICA Commission on Visualization and Virtual Environments from a number of perspectives. Research on representation underpins many of the other issues addressed in accompanying papers. Initially, the structure and content of the geospatial databases from which the representation is drawn, and computational methods applied to them, will have an impact on the nature of the visualization process. Further, the role of the user in perceiving the resultant representation has been stressed. Many new (or understudied) cognitive issues are raised when dynamism, senses such as hearing and touch, immersive displays and avatars are incorporated into the cartographic representation. The implied role of interactivity is also a vital part of the display, involving the impact of navigational controls, user input and behavior when representations are supplemented by feedback loops.

The design and implementation of an effective user interface must consider means of conveying representations (by vision, sound or touch), methods of displaying extra information (e.g., legends and scale), and techniques of informing the user of interactivity possibilities.

Summary

The previous sections of this paper have addressed some of the large number of research issues associated with contemporary progress in cartographic representation. This summary presents five broad themes that we propose as a structure for proposed research in this area.

- *Characteristics of data*. Which data characteristics are important for determining appropriate representations for visualization? Effectively, we must determine what we need to know about the data to represent then successfully. It may be possible to develop some rules (based on semantics and embedded as metadata) in order to ensure that representations are valid and to avoid nonsensical displays.
- *Extending representations*. We have identified considerable scope for using less traditional mappings between data type, model and representation in visualization, particularly for qualitative, intangible and conceptual data. In addition, new techniques of data collection and new types of data may require an extension of representation method. What advantages are there in extending representations using sound and haptic methods? The mechanics of linking representation method with novel data models and with intelligent databases, for example those that incorporate structures designed for display, navigation, streaming, mining or level of detail, need consideration.
- *Representation purpose*. Similarly, we need to ensure that representations are valid for particular tasks. A fundamental step toward meeting this goal would be development of a comprehensive typology of geospatial data handling tasks. This will firstly provide a framework for developing new forms of representation, by identifying data handling tasks that are currently not well supported, as well as a framework for comparing alternative forms empirically. Secondly, it will enable us to identify which representations are appropriate in which circumstances and match them to tasks (and users and data), thus enabling the development of systems that help users select appropriate representation forms to meet their needs and systems that can make such selections automatically.
- *Levels of use and interactivity*. We need to continue to achieve the high level of interactivity that the process of visualization requires. Advances in the related areas of data models, databases and interfaces improve our chances of accomplishing this. Continual assessment of the interactive graphical techniques available, and the map behaviors that we can achieve will ensure the currency of cartographic products for visualization. Links to cognitive research issues are clearly important here.
- *Developing technologies*. A constant feedback to the more theoretical issues above is the state of technology. How do new technologies for collection, dissemination, display and organization of geographical data modify these issues? As technology advances, the utility and suitability of representations develops. In addition, there are new users, new tasks and new applications that can take advantage of cartographic representations.

We suggested at the start of this paper that there are new things to represent, new methods of representation, and a need for comprehensive understanding of both. The first of these requires an emphasis on geographical enquiry; the second emphasizes technology; the third considers the theoretical-philosophical basis of cartography. This paper has examined the research avenues of greatest importance in addressing these issues. Some focus on implicit and contemporary practice in new media; others are freshly provoked by the new technologies that have been outlined. Some are related to the novel treatment of cartographic representations using techniques previously considered only for non-spatial or numeric data; others are prompted by the application of traditional cartographic practices to new media. Some address multi-disciplinary aspects and require innovation from a range of research workers; others are related to specifically cartographic issues. Cartographers, either alone or in concert with other scientific researchers, have the potential to solve these problems and their solution will have a significant impact on the nature and practice of cartography, scientific visualization and the applications domains that use our representation methods.

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