Pergamon

Computers & Geosciences Vol. 23, No. 4, pp. 335–343, 1997

Printed in Great Britain

PII: S0098-3004(97)00018-6 0098-3004/97 $17.00 + 0.00

GUEST EDITORIAL

EXPLORATORY CARTOGRAPHIC VISUALIZATION: ADVANCING THE AGENDA

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Abstract—An approach to the visualization of georeferenced data is presented. This approach is rooted in cartography and emphasizes the use of visual methods in research and decision making. Several definitions proposed within cartography are considered and the links between "cartographic" visualization and scientific visualization more generally are discussed. From this base, a perspective on visualization is articulated in which attention is directed to the goals for use of maps and related georeferenced displays. We argue that a use-based approach is needed in order to develop information processing environments appropriate to distinct stages of scientific research and decision making. The paper concludes by proposing a set of research problems that are prompted by taking a use-based approach to visualization, and then outlining the selection and context of the papers in this special issue. © 1997 Published by Elsevier Science Ltd

Key Words: Cartography, Visualization, Dynamic maps, Exploratory data analysis.

INTRODUCTION

The nature of maps and of their use in science and society is in the midst of remarkable change — change that is stimulated by a combination of new scientific and societal needs for geo-referenced information and rapidly evolving technologies that can provide that information in innovative ways. A key issue at the heart of this change is the concept of "visualization."

At one level, all mapping can be considered a kind of visualization — in the sense of "making visible." From this perspective, cartography has always been about visualization. Over the past several decades, cartographers have devoted considerable attention to understanding how *presentation* maps work to make aspects of the world visible—what Freitag, 1993 terms the "communication function" of maps. We know relatively little, however, about how maps that facilitate thinking, problem solving, and decision making work (uses that, according to Freitag's typology, are representative of the "cognitive function" and the "decision support function" for maps), nor what the implications of "working" are in these contexts (implications associated with Freitag's "social function" and Török's "social context" (Török, 1993), — the latter derived largely from Harley's (Harley, 1988, 1989) approach to the ideology of mapping). It is to the cognitive and decision-support functions that much of the new geo-information technologies are directed — particularly those technologies which include maps having dynamic and interactive components. It is also in these functions that scientific visualization and cartography share the greatest overlap (MacEachren and Monmonier, 1992).

Whereas cartographers can argue that we have always been involved with visualization (see Freitag, 1993; Rimbert, 1993), treating current conceptions of visualization as "nothing new" ignores the most important implications of the alternative definitions of visualization used beyond the discipline. These new definitions of visualization are linked to specific ways in which modern computer technology facilitates the process of "making visible" in real time (see Taylor, 1991, 1994). The ability to prompt instantaneous changes in maps results not only in a quantitative difference in the number of things a user can make visible, but a qualitative difference in the way users think — and in turn in the way maps function as prompts to thinking and decision making (Wood, 1994).

Cartography as a discipline has a significant stake in the evolving role of maps within systems for scientific visualization, within spatial decision-support systems, within hypermedia information access systems, and within virtual reality environments. Cartography has much to offer the scientific community through its long history of design and production of visual representations of the Earth, its knowledge of geographical (and cartographical) information systems, and its experience with linking digital and visual geographic representations. On the other hand, cartography has much to gain from collaborations with the wider scientific visualization community where approaches to interactive computer tool development, interface design, three-dimensional computer modeling, and related methods and technologies are more fully developed.

In 1995, the International Cartographic Association (ICA) established a new Commission's on Visualization, in part, to facilitate connections among cartographic researchers around the world and researchers in other disciplines working on various aspects of scientific visualization [for details see the Commission's WWW site at: http://www.gis.psu.edu/ica/ICAvis.html]. Among the Commission's "terms of reference" for its initial four-year term are the following: (1) to study and report on the changing and expanding role of maps in science, decision making, policy formulation, and society in general due to the advent of *intelligent* dynamic maps that are designed as *visual thinking/decision-support* tools; and (2) to investigate and report on the links between *scientific visualization* and *cartographic visualization* and identify ways to facilitate exchange of ideas between cartographers and others working on problems in visualization.

This special issue of *Computers & Geosciences* was initiated to serve as a benchmark for progress on georeferenced visualization to-date, and as a prompt to the international cartographic and geoscientific communities to initiate new and expanded visualization research efforts. The co-editors (Alan MacEachren and Menno-Jan Kraak) are chair and co-chair, respectively, of the ICA Commission on Visualization and this issue was sponsored by the Commission. Details of the paper solicitation and review process are included later).

VISUALIZATION IN CARTOGRAPHY: EVOLUTION OR REVOLUTION?

Use of the term visualization in the cartographic literature can be traced back at least four decades (Philbrick, 1953). It was the 1987 publication of a report by the U.S. National Science Foundation, however, that established a new meaning for this term in the context of scientific research (McCormick, Defanti, and Brown, 1987). The report, produced by a committee containing no cartographers, emphasized the role of computer display technology in prompting mental visualization — and subsequent insight. Scientific visualization has, thus, been defined as the use of sophisticated computing technology to create visual displays, the goal of which is to facilitate thinking and problem solving. Emphasis is not on storing knowledge but on knowledge construction. In relation to the spatial information processing goals for maps delineated by Rimbert (1993), "spatial analysis" and "spatial simulation" could be considered prototypical components of scientific visualization. Rimbert's "travel guide," "spatial inventory," and "secondary information source" goals, in contrast, would be considered (at least by some researchers in scientific visualization) to be ancillary to the visualization process — although they may benefit from information processing and display methods developed to support the core visualization goals.

Following publication of the McCormick report on visualization in scientific computing, several cartographers took up the challenge of trying to grapple with the cartographic implications of this new (or renewed) reliance on visual representation in science. DiBiase (1990) borrowed from the exploratory data analysis (EDA) literature of statistics to propose a graphic model of stages in map-based scientific visualization applied to the earth sciences. The model presented visualization as a four-stage process consisting of two private visual thinking stages (exploration and confirmation) and two public visual communication stages (synthesis and presentation). An intent of the model was to encourage cartographers to direct attention to the role of maps at the early (private) stages of scientific research where maps and map-based tools are used to facilitate data sifting and exploration of extremely large data sets.

MacEachren and Ganter (1990), in a parallel effort, developed a simple cognitive model to identify key parts of the user-display interaction that occurs during exploratory map-based visual analysis. Their emphasis was on developing cartographic tools that prompt pattern identification and on the potential for visualization errors (errors that are similar in nature to the Type I and Type II errors associated with traditional statistically based hypothesis testing). The related topic of visualizing data quality/reliability has proved to be a particularly active research direction within cartographic visualization (e.g. MacEachren, 1992; Beard and Buttenfield, 1991; Buttenfield and Beard, 1994; Fisher, 1994; van der Wel, Hootsman, and Ormeling, 1994). MacEachren (1995) has subsequently grounded the pattern identification approach to visualization in an integrated cognitive–semiotic conceptualization of how maps (and other geo-referenced displays) work as visualization tools and has applied that approach to the design of visual interfaces directed to reliability representation.

Although these conceptions of visualization in cartography put emphasis on the private–cognitive processes of visual thinking (particularly those associated with scientific hypothesis formulation and confirmation), Taylor (1991) directed attention to the place of visualization in the structure of cartography as a discipline. His approach presented visualization as the intersection of research on cognition, communication, and formalism (with the latter implying strict adherence to rule structures dictated by digital computer systems). In a recent revision of this approach, Taylor (1994) made it clear that he does not equate "visualization" with "cartography." Instead, he argues for a view of visualization as a distinct development in cartography, and in science in general, that will have an impact on three major aspects of cartography — aspects that he defines as the sides of a "conceptual basis" triangle (cognition and analysis, communication, and formalism).

EXPLORATORY CARTOGRAPHIC VISUALIZATION: EMPHASIZING MAP *USE*

Building from the perspectives on georeferenced/cartographic visualization outlined above, a conception of visualization emphasizing *use* of visual displays was developed (MacEachren, 1994). This continually evolving map use-based approach to visualization has been a driving force behind creation of the ICA Commission on Visualization and the initial research activities initiated by that commission. The approach treats map use as a "space" referred to by MacEachren as [CARTOGRAPHY]^3 — a reference to the three axes along which map use was characterized (Fig. 1). In this space, visualization is considered to be the complement of communication. All map use involves both visualization (defined loosely as the prompting of visual thinking and knowledge construction) and communication (defined loosely as the transfer of information), but map use can differ considerably in which of these activities is emphasized. The axes of the use-space are delineated as private versus public, high interaction versus low interaction, presenting knowns (i.e. simple information retrieval) versus revealing unknowns.

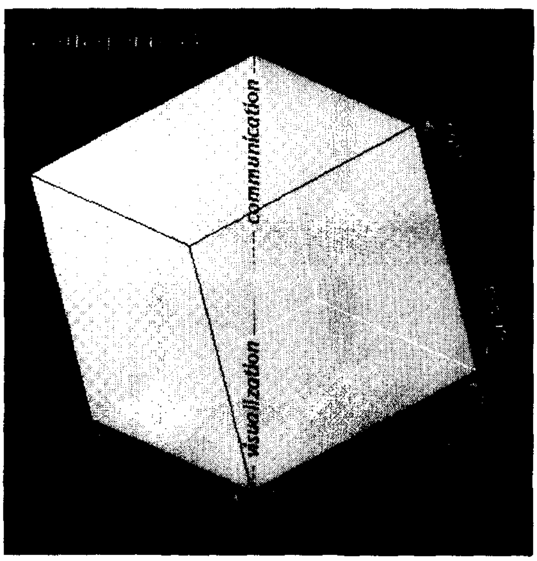

Figure 1. (CARTOGRAPHY)^3 — representation of three-dimensional "space" of map use. Relative emphasis on visualization and communications activities is depicted. Axes relate to audience or user of map (ranging from private to public), objectives of use (from revealing unknowns to presenting knowns), and degree of interactivity with map or mapping environment (from high to low). (Reproduced from MacEachren, 1994 fig. 1.3, p. 6, by permission.).

Past communication-oriented cartographic research has emphasized the use of static maps designed for public consumption with the emphasis on extracting specific pieces of information (e.g. research on communication effectiveness of textbook or topographic maps). As a complement to this relatively long tradition of communication research, the ICA Commission on Visualization is targeting the opposite extreme of the map use cube — with emphasis on the role of highly interactive maps in individual and small group efforts at hypothesis generation, data analysis, and decision-support.

As Kraak (in press) has discussed, strategies must differ for design of visual displays and display systems to support map use at various positions in the use-space identified. Building from the previous use-oriented discussion of visualization, combined with both Kraak's delineation of visualization strategies and DiBiase's (DiBiase, 1990) conceptions of the stages that underpin EDA adapted to geo-referenced data, four *use goals* can be recognized. Each requires its own approach, characteristics of which are implied by position of the goal within the use cube (Fig. 2). Since a particular map, whether static or dynamic, might be used to meet all of the goals, the distinction between the goals is based, not on types of map, but on the audience, data relations, and interaction level that is typical for pursuit of the goal. The location of the spheres in the diagram represents current typical applications of visualization methods to each goal. Over the past decade, interactivity has become increasingly important in strategies to achieve all goals, and we envision a future in which the dominant strategies for pursuing all four goals are arrayed along the left wall of the use cube — a future in which high interaction is as typical of presentation uses as of exploration uses.

Visualization to explore, in order to examine unknown and often raw data creatively, is the dominant strategy at the *private–high interaction–exploration of unknown* corner of the use cube (Fig. 2). In several applications, such as those dealing with remotely sensed data, there are abundant (often temporal) data available. Questions such as "what is the nature of the data set?", "which of those data sets reveal patterns related to the current problem studied?", and "what if...?" have to be answered before the data can actually be used in a spatial analysis operation. Required to support mapping strategies here, are functions to allow the user to explore the spatial data visually (e.g. by animation — Fig. 3), to identify relationships among variables (e.g. by linked views — Fig. 4), and to

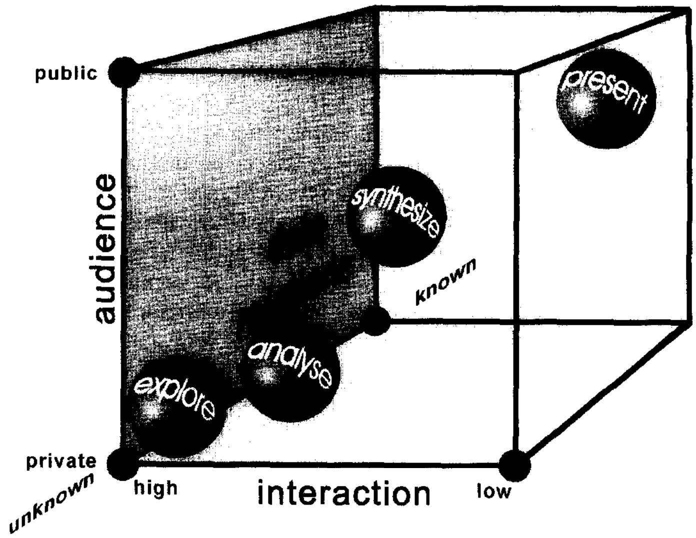

Figure 2. Goals of map use. Sequence of goals that can be facilitated by visualization methods are arrayed in map-use cube. Here, emphasis is on distinguishing among use goals that may require different visualization strategies.

"see" data from multiple perspectives (both spatially and conceptually). Therefore, specific visual exploration functions and tools are needed that facilitate use of these "new" dynamic mapping methods. It also should be noted that, in a data exploration environment, it is likely that the user, at least at the start of a visualization session, is unfamiliar with the exact nature of the data, a situation that calls for flexible visualization that can be adapted by the user.

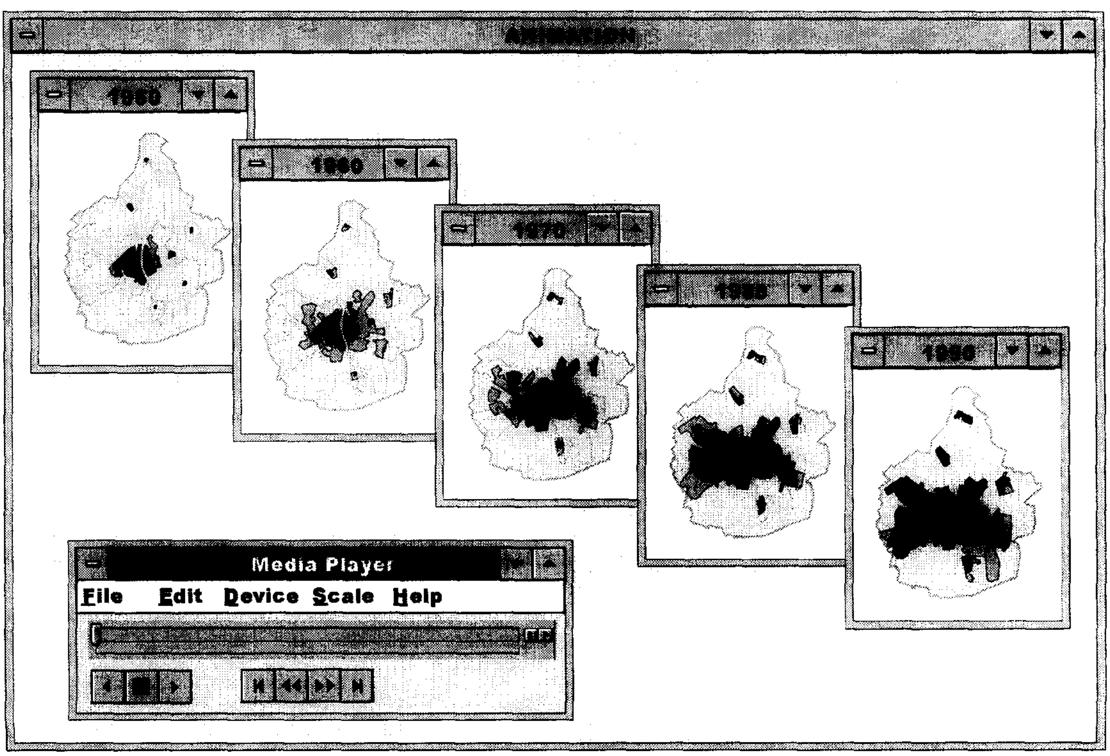

Figure 3. Depiction of simple interactive animation designed to support visual exploration of spatio–temporal data set.

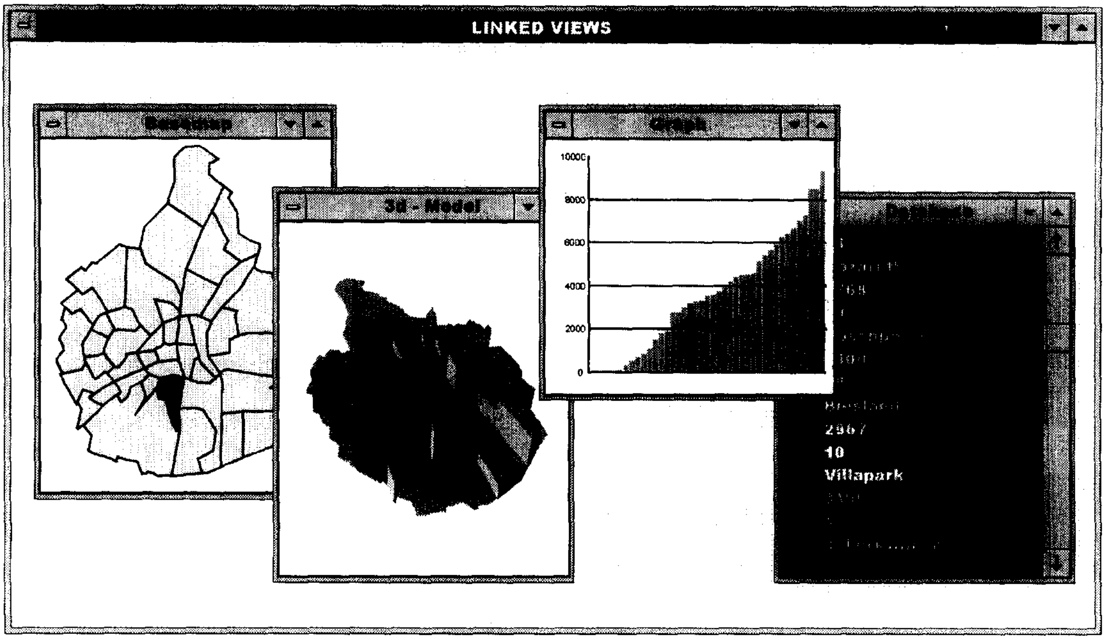

Figure 4. Depiction of interface using linked views as method for exploring relationships among variables.

Visualization applied to analysis generally involves manipulation of known data in a search for unknown relationships and answers to questions. The use strategies here also emphasize relatively private use that is facilitated by interactive systems. In a planning environment, for example, the nature of two separate data sets might initially be fully understood, but not their relationship. A spatial analysis operation, such as (visual) overlay, combines both data sets to determine their possible spatial relationship. Questions such as "is there a spatial correlation", "what is the best site?", or "what is the shortest route?" are typical of analytical uses of visualization tools and methods. Required to support these uses are functions to target individual map components to extract information from them (e.g. the EDA method of "focusing"), and functions to process and manipulate that information.

Visualization applied to synthesis of information moves the emphasis away from single investigators toward groups (perhaps of specialists) and from revealing unknowns toward presenting knowns. With synthesis, however, there is still considerable chance for new insights. Questions to be answered here include: "what general result(s) does the analysis suggest?" "how different are a pair of problem solutions?" or "how can we best summarize many, perhaps conflicting, results?" Functions required are ones that extract the most salient patterns and relationships from a data set and display them as a coherent abstraction of the exploration and analysis process. Tools to filter out local details, random noise, etc. are required. Monmonier's (1992) concept of "summary graphics" provides a model strategy for the generation of displays that support synthesis. Both he and DiBiase (1990) emphasize giving up detail in exchange for a useful abstraction as a key to effective synthesis. Geoinformation use that emphasizes synthesis, just as exploration and analysis, can benefit from interactive tools that allow a user to experience more than one possible synthesis, perhaps ones that emphasize different parameters of a problem or different philosophical perspectives on that problem.

Presentation is often equated with cartographic communication (in the information-theory sense that underlies the communication model approach to cartography). Presentation can, however, include both transfer of some predetermined "message" and the prompting of new insight on the part of the person who experiences or accesses the presentation. Visualization applied to presentation emphasizes public use and the "presentation" of information that is largely known to the information designer, but not to the user of the presentation. Similar to the goals detailed previously, presentation can derive considerable benefit from use of interactivity. Thus the sphere used in our diagram to characterize presentation uses of visualization methods is not at the extreme opposite corner of the use-space from the one representing exploration. As Cartwright's analysis of WWW impact on cartography makes clear (Cartwright, 1997, this issue), presentation uses are rapidly incorporating interactivity. Whether interactive or not, presentation strategies should emphasize the transfer of spatial knowledge (rather than creation of new knowledge). If cartographic displays are well designed to support presentation uses, the results of spatial analysis operations can be easily understood by a wide audience. Design strategies must support queries such as "what is?" or "where is?", and "what belongs together?". The cartographic discipline offers a comprehensive cartographic "language" with associated rules, strategies, and conventions with which to generate maps supporting these uses (Kraak and Ormeling, 1996). Depending on the nature of a spatial distribution, this language will suggest particular presentation mapping solutions. A number of authors have proposed methods to formalize these rules into expert systems that support dynamic visualization (Buttenfield and Mark, 1991; Jung, 1995). Caution must be exercised, however, when applying cartographic rules developed for presentation to the design of visualization environments intended to support the full range of use goals identified.

RESEARCH DIRECTIONS FOR EXPLORATORY CARTOGRAPHIC VISUALIZATION

The evolving conceptualization of visualization, as it relates to cartography and to science in general, raises a wide variety of new research questions for cartography, as well as for other sciences with an interest in geo-referenced visualization. The ICA Commission on Visualization has identified a set of specific research goals. They are listed below, along with representative citations to published literature that serve as a starting point for tackling these goals.

1. Investigate the implications of a change in cartographic emphasis from a focus on designing optimal maps to one that favors mapping systems that facilitate multiple perspectives — see Monmonier (1991) for an argument that single map solutions should be considered unethical.
2. Develop a conceptual model and associated tools for the visualization of spatial–temporal process information — see Slocum and Egbert (1991) for a review of relevant work in cartographic animation, Board (1993) for discussion of spatial process as one of the main theoretical areas in cartography requiring attention, and Kraak and MacEachren (1994) for a framework through which to explore visualization of spatial data's temporal component.
3. Develop a conceptual model and associated tools for the visualization of data quality/reliability information — see Buttenfield and Beard (1994) and van der Wel, Hootsman, and Ormeling (1994) for alternative suggestions about where to start.
4. Study of methods for, and implications of, linking cartographic visualization tools to GIS — see Knapp and Carron (1994) for one attempt to achieve this link.
5. Explore the impact of map-based spatial decision-support tools on decision-making strategies and on the outcome of decision making — see Asche and Herrmann (1993) for a description of a map-based visualization/decision support system, Armstrong and others (1992) for a taxonomy of decision–display types, and McGuinness (1994) for empirical methods suited to identifying strategies for use of visualization tools in decision making.
6. Study the potential of three-dimensional representation tools and the corresponding implications of both three-dimensional display and the associated general trend toward realism (versus abstraction) in scientific representation — see Fisher, Dykes, and Wood (1993) for a discussion of 3D visualization tools.
7. Address implications, for our approaches to map design, of the ability to link many representation forms together in hypermedia documents (e.g. maps, graphs, text, audio narratives, sonic data representation, etc.) — see work by Cartwright (1994) for ideas concerning links between visualization and hypermedia.
8. Investigate alternative computer interface design strategies as they relate to use of visualization tools for hypothesis formulation and decision support — see Lindholm and Sarjakoski (1994) for a conceptual outline of some possibilities.

Most of these research goals are addressed, either directly or indirectly, in the research detailed in the present volume. At its annual meeting (in Delft, The Netherlands, in September, 1996) the Commission on Visualization launched an additional research initiative, directed to desktop virtual reality applied to geo-referenced data. This initiative is part of the "Carto Project" collaboration initiated recently between the Commission and the Association for Computing Machinery Special Interest Group on Graphics (ACM-SIGGRAPH). Details of the Carto Project and the VR initiative can be found on the Commission's WWW site [http://www.gis.psu.edu/ica/icavis/vis-acm.html].

SPECIAL ISSUE: PROCESS AND CONTENTS

Paper solicitation and review process

The idea for a special journal issue dealing with *exploratory cartographic visualization* was developed during the 1995 meeting of the International Cartographic Association in Barcelona. The primary goal identified for the special issue was to provide readers with a coherent set of papers that present research dealing with advances in map-based visualization of geo-referenced data. Papers were solicited to cover three key aspects of this research: (1) theoretical concepts that underpin extension of cartographic principles to dynamic environments for supporting research and decision-making, (2) implementation of concepts in exploratory cartographic tools, and (3) innovative applications of those tools. A second goal (and the goal behind the electronic component of the special issue) was to provide readers with dynamic illustrations that represent the dynamic methods and tools being discussed (and to provide authors with a better way to present their research about these methods and tools). This latter goal lead to the decision to prepare a combined print–electronic journal issue. Graeme Bonham-Carter, the editor of *Computers & Geosciences*, along with the journal's publisher were receptive to this plan.

Paper solicitation was organized to coincide with the Delft ICA Commission on Visualization meeting mentioned above. For that meeting, researchers from around the globe working on various aspects of georeferenced visualization were invited to submit "working papers" for presentation and discussion. The working papers were submitted for discussion as WWW documents. Authors were not required to attend the Commission meeting to have their paper discussed and not all working papers were planned for submission to the issue. Those attending the Commission meeting were given the WWW address for papers three weeks prior to the meeting and asked to review all papers submitted. During the Commission meeting, each working paper was accessed live from the author's home site, the author (if present) or one of the others in attendance (if no author was present) provided a brief summary, and that summary was followed by discussion. Notes on those discussions were compiled and forwarded to authors. Authors of working papers that were favorably received, intended for the issue, and a good match with the issue goals were invited to expand their working paper into a full article for submission to the special issue.

All full papers were reviewed, in electronic form, by two referees. Our time schedule for this process was tight. We would like to thank all authors, the commission members who participated in discussion of working papers, and the many reviewers involved for responding promptly and making the issue possible.

Structure and contents of the special issue

Papers in this issue can be grouped according to the kinds of visualization methods or visualization environments focused on by the authors. We identified three main categories: Exploratory Spatial Data Analysis, hyperlinks and the World Wide Web, and Virtual Reality.

Exploratory spatial data analysis. The set of papers emphasizing Exploratory Spatial Data Analysis can be further grouped into three sub-categories based on the visualization methods used or kinds of information they are applied to: brushing and linking, non-temporal animation, and temporal animation.

Brushing and Linking: Dykes, in "Exploring spatial data representation with dynamic graphics" presents an approach to dynamic cartography via the Tcl/Tk graphical user interface (GUI) builder. This approach and development environment allows the user to explore spatial data sets interactively through a combination of methods, with an emphasis on linked views. In their contribution "Dynamic graphics in a GIS: More examples using linked software" Cook and her colleagues describe the linking of two existing software packages (ArcView and Xgobi) to provide EDA tools that are dynamically linked to a GIS.

Non-temporal Animation: The three papers in this category all use animation as a method for representing uncertainty in spatial data. Both Ehlschlaeger and his colleagues with "Visualizing spatial data uncertainty using animation," and Davis and Keller with "Modelling and visualizing multiple spatial uncertainties" have developed an approach to measure and visualize uncertainty and have applied the approach to representing uncertainty in terrain and soils representations, respectively. Evans, in "Dynamic display of spatial data-reliability: does it benefit the map user?," has assessed the use and usefulness of maps containing graphically depicted reliability information (with land cover maps as the application focus).

Temporal Animation: In "Time-series animation techniques for visualizing urban growth" Acevedo and Masuoka present results of a project to develop time-series animations depicting several data sets for the Baltimore–Washington area in the U.S. Attention is given to issues of temporal interpolation for data of different kinds. Mitas and colleagues, in "Role of dynamic cartography in simulations of landscape processes based on multivariate fields" use animations for advanced visual analysis of multivariate georeferenced data by displaying multiple surfaces and volumes in an appropriate projection of 3D space together with vector and point data.

Hyperlinks and the world wide web. Three papers in the issue emphasize hyperlinks and the World Wide Web. Cartwright, in "New media and its application to the production of maps" presents a conceptual approach to the various types of WWW products which could be developed for the delivery of spatial information in a different, and complementary manner to traditional spatial visualizations. In "Principles of hypermaps" Kraak and van Driel describe the functionality of a hypermap, a georeferenced hypermedia system. In their prototype, individual hypermedia components are linked with respect to each other and the map. Fernandes and colleagues, in "Visualization and interaction tools for aerial photograph mosaics" propose a set of navigation, interaction, and visualization tools to access and use a digital spatial library based on mosaics of digital orthophotos of Portugal.

Virtual reality. The final grouping consists of two contributions that deal with application of virtual reality methods to georeferenced data display and exploration. Fairbairn and Parsley, in "The use of VRML for cartographic presentation" introduce the concept of the Virtual Reality and its terminology (from a cartographic perspective) and illustrate the potential of Virtual Reality Modelling Language (VRML) with a prototype VRML campus map. In "Cognitive spaces and metaphors: a solution for interacting with spatial data," Neves and colleagues present a new metaphor for interacting with spatial information, the (GIS) room, which incorporates devices and information designed to provide a more natural interaction with a GIS.

The issue concludes with a commentary from Theresa-Marie Rhyne that considers cartography as a bridge between developments in scientific visualization and GIS. Arguments are presented for collaboration on standards for virtual reality tools that take georeferenced information into account.

CONCLUSION

We believe that this issue is the first combined print–electronic issue of any journal to be directed to visualization of georeferenced data. The motivation has been to stimulate cross-disciplinary sharing of research results and to provide a publication outlet that allows authors to illustrate their approaches to dynamic interactive visualization with dynamic interactive illustrations. This opportunity has brought together contributions from six countries representing research efforts within cartography, geography, geomatics/geoinformatics, land information, computer science, statistics, remote sensing, and environmental systems analysis. It is our hope that this publication stimulates interdisciplinary collaboration directed to exploratory visualization of georeferenced information. Those interested in information about (or becoming involved in) initiatives sponsored by the ICA Commission on Visualization are encouraged to contact one of the co-editors of this special issue.

CD-ROM

The CD-ROM included with this issue contains enhanced versions of all papers. Text is formatted to take advantage of the electronic medium and, in a few cases, supplemental notes not contained in the print version are included. The most important difference between the print and electronic version of the issue, however, relates to illustrations. The electronic version of most papers contains color illustrations that are not included in the print version (or are included in monochrome). In addition, most papers in the electronic version include dynamic illustrations, thus allowing readers to view animations discussed in the paper and/or manipulate interactive maps

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