Representation and its relationship with cartographic visualization: a research agenda

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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.

Introduction

Graphical presentation of information has a long history, and some of the earliest extant graphical presentations are 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) that there are new methods of representation; and c) that 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. Further research into representation is one of those challenges.

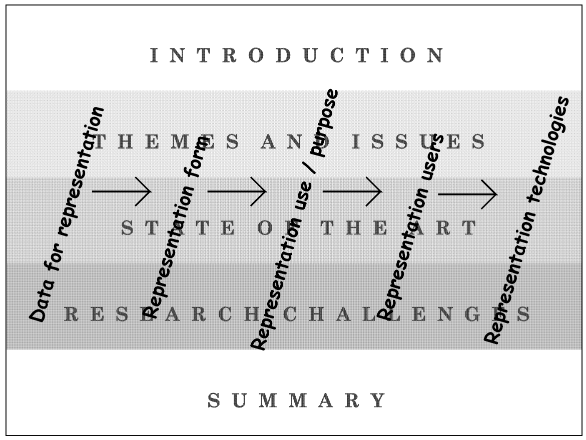

Figure 1: The structured approach of this paper to representation issues

This paper develops a research agenda that addresses 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 set the scene for further discussion on the current *state of the art*. This section specifically examines the nature of contemporary cartographic representation, the variation in data that can be represented, and the tasks to which representations are applied. A number of *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* proposes five broad themes that together delineate the fertile ground for research in the area of cartographic representation. Within each section several aspects of representation can be separately identified and discussed. Five of these are presented: the nature of what kind of **data** and phenomena are to be represented, the **form** of representation chosen (for example, 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. These aspects have provided the structure for each section within this paper (*Figure 1*).

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. In order to handle and view this information, a suitable means of transforming it into recognizable graphical entities is required. The possibilities for achieving these transformations for the digital and graphical representation of spatial information are developing rapidly. In the context of visualization we need to advance ways of transforming information about the world into models suitable for digital and *carto*graphic representations that are designed for, and facilitate, 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. The models that meet these requirements are changing significantly themselves.

Defining representation and methods of representation

It is possible to regard modeling itself as a form of representation, although for this discussion it is assumed to be the data-handling step prior to subsequent representation. Modeling of spatial data is undertaken to ensure that data are captured, held, managed and manipulated in a suitable way for the application in hand. The application may involve representation of all types, for archival, communication and/or analytical purposes. The visual representation of spatial data is the focus of this paper and, in particular, the interaction of contemporary aspects of visualization (broadly) and geospatial visual representation is addressed. All subsequent references to representation should be interpreted as referring to *visual* representation unless otherwise qualified.

Cartographic representation is defined (for the purposes of this paper) as the transformation that takes place when information is depicted in a way that can be perceived, encouraging the senses to exploit the spatial structure of the portrayal as it is interpreted. These representations are usually graphical, but may also be haptic or audible, or involve elements that mix other senses with sight.

Cartographic representation encompasses the totality of the [Cartography][3] structure developed by MacEachren (1994a) – thus, all mappings of geospatial information into perceptible forms. The emphasis of the agenda put forward in this paper is on the part of the cube labeled 'visualization': the representations discussed here 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.

Although each visual experience based on graphics is unique to the user[1] and the information portrayed, we are able to use graphics effectively to learn about the world by structuring, and making connections among, our previous experiences (both with graphics and in the world). We recognize patterns and obtain insights from graphical representations in a 'non-serial' way, and use visualization as a non-linear means of obtaining knowledge (Lloyd, 1997). There is a connection, therefore, between the real world and its iconic representation in map and more schematic forms – an inherent

1 Robinson and Petchenik (1976) distinguish a (map) 'percipient' - one who obtains information by looking at a map - from map 'users' or map 'readers' who use maps for a specific purpose. We employ the term (map) 'use' here, however, to refer to the broader scope of all interactivity with a cartographic representation; and therefore a 'user' is one who engages in such interaction.

'spatialization' experienced by all humans. There is value in researching geographical and associated visualization methods that address information exploration and presentation in the *spatial* environment. Of concern to such research is the central role of cartography as a core component in the visualization of this spatial domain and also across the wider realms of scientific enquiry and exploration.

Themes and Issues

Issues in representing spatial data

Associated with geospatial information representation and exploration are issues related to the nature of the underlying geospatial data – its differing types (e.g. multivariate, spatio-temporal, uncertain), its differing properties (e.g. scale, meaning), and its differing methods of collection and storage (e.g., satellite remote sensing, mail survey, field GPS). We may require different representations for different types of 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 spatial 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, 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: Davis and Keller, (1997) Pang et al., (1997) and Buttenfield and Beard (1994) describe some techniques of quality representation for conventional mapping. This is of considerable importance when data are being incorporated into the representation from a range of sources, both known and unknown (Mahoney, 1999).

The types of phenomena that are being recorded, data that are being collected and 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, and the masses of data that are being accumulated are ripe for representation using cartographic techniques and investigation with visualization. Examples include logged positional data from global positioning systems and automatically captured digital imagery. As the US FCC considers requiring that all cellular telephones be equipped with GPS receivers we have new opportunities for recording, storing and analyzing information about geographical location and behavior at the individual level. Potentially this can provide far more information about the geography of the population than even the precisely geo-coded address model. Locations are likely to be time dependent, cyclical, multi-scale and predictable with varying accuracy and levels of confidence over space and time. Examples of how such 'time-geographies' are addressed using space-time visualization are given in Hedley et al. (1999). A further application is the use of permanent video stations to study traffic congestion in cities or coastal processes across the globe. With the latter, oblique (from a coastal tower) digital imagery of wave patterns approaching a beach can be averaged, and rectified for interpretation. Series of such images can be used to create movies showing changing wave patterns that relate to the changing underlying topography of the nearshore zone, whilst the 'stacking' of horizontal sections of oblique images of the shoreline allows for the monitoring of temporal changes in the behavior of the coastline (Aarninkhof and Holman, 1999). But how do we store such data in order that we can manage it efficiently, portray it efficiently, interactively visualize it, re-configure, re-express it, and combine it with other sources, and what are the best methods for representing it cartographically?

It would be useful to have access to a comprehensive typology of 'mappable things' – phenomena which can be represented on maps. A distinction to note here is between data (measurable occurrences) and phenomena (underlying concepts or real world objects, such as a traffic jam or hurricane). Although data characterize phenomena and form the basis of our representation, they can look identical within databases (consider the <x,y,value> triple which could refer to point sources of temperature measurement, or could measure the intensity of an earthquake at a point). We cannot consider a representation method for the data until we have fully comprehended the phenomenon. The establishment of formal metadata standards is a step toward 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), Tufte (1983), Mackinlay (1986) and Cleveland (1993) for graphics, and extended by Krygier (1994) for sound, and by MacEachren (1994b; 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, therefore, 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 spatial data in its widest sense therefore involves issues of what form representations should take and how representations are used.

The impact of cartographic representations is often (some would contend *must be*) based upon conventional interpretative aids such as legends and scales. Kraak et al. (1997) and Buziek (2000a) have examined legends and scales in animations and other visualizations. In some cases such elements must be reactive (changing with a zoom operation, for example) or interactive (legend content changing dependent on user choice of display and map content changing dependent on user manipulation of the legend parameters). Legends and scales need to reflect the graphical variables used in representations, but a form of 'legend' may also be required to assist in interpretation of data represented using non-visual methods. Here, therefore, is another issue associated with representation: the whole area of design must address the development of non-visual methods of representation. Research is, therefore, needed on perceptualization, considering multi-sensory methods for data and information representation.

In addition, contemporary representations often display 'non-conventional graphics', moving beyond traditional static, two-dimensional mapping. A whole range of map behaviors are possible in the evolving world of dynamic mapping where the previously universal 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 in order that 'good practice' can be identified and formalized. In order to design effective graphics, we need to understand the role and nature of dynamic displays.

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 in this way is useful, providing a framework upon which research can be built to help us deploy new methods of representation effectively and efficiently.

Representation and the purpose of mapping

Cartographers have addressed and will continue to address the role of map-based representations for a wide range of tasks (e.g. depicting data uncertainty or three-dimensional scenes) and for differing use contexts, many of which are relevant to and have been addressed from different perspectives by researchers in other fields. 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 spatial 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 link to other data from within the representation.

A variety of problem solving and data exploration tasks is addressed using cartographic representations. Therefore, formal links between visual analysis and statistical analysis, and between hypothesis generation and hypothesis checking need to be established (topics addressed in Gahegan et al., 2000). Such links have the potential to result in visualization methods that produce added value in scientific research, thus to move visualization away from an operation 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 spatial data representations and our goal of insightful visualization, supported by future methods of representation, is the potential to enable a pro-active 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 spatial 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. As explained later in this paper, the practical outcome of cartographic practice relies on the abstraction of spatial 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 spatial data at multiple scales and for varying purposes. The experience of addressing problems of map generalization provides approaches through which cartographers can efficiently create multi-scale representations of spatial data in a variety of forms.

Aspects of 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 spatial information, such as positioned sound, truly three-dimensional methods of projection and the ways in which these methods work in combination and relate to multi-user modes of interaction and traditional map elements such as symbology and the provision of legends and scales. In addition, we should be able to sense the feedback and interactivity involved. How does the user interact with sonification and with dynamic displays? What type of interactivity is appropriate in which types of representation and how useful and effective is it? Shepherd's (1995) typology of dynamism in maps, and his range of 'observer-related' map behaviors provide a useful framework and starting point. How do we ensure that all these developing possibilities link data, user and task in an appropriate and beneficial manner? Finally we need to ascertain the role of user insight in accessing, using and gaining 'added-value' from new representations.

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 VR and its dynamic nature when used with representations is worthy of further investigation, in particular the impact on the viewer of realistic and interactive representations. The effect of multi-user environments is also of considerable interest as these are very recent in development and application. 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 (for example) between novice, or casual, users and experts. Adaptive representations are needed that take account of these differences. In addition, perceptual deficiencies, such as color deficiencies, may lead to the need to consider alternative representations. Also relevant to the visualization corner of [Cartography][3] (although not stressed in the original presentation of that model), is the distinction between representations for single users and those for multiple, group viewing. It is clear that there now exist collaborative tools that allow groups to collectively construct personalized representations, so it is not the number of users which is of most relevance, but the tasks to which the resultant representations are applied.

Research and development in studies investigating user/representation interactions is also covered in other papers in this volume that deal with interfaces and with cognitive aspects. One result of the combined attention to this issue 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.

Technological themes and representation

It is important to have knowledge of the potential developments in the actual technology on which many new cartographic media rely; a range of technologies is being applied to visualization. We are now able to represent data dynamically, or with sound, or over the Web, or using mobile communications (such as developments in 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 quickly the scenarios in which these representation methods and forms are a valuable addition to visualization, and subsequently how we best incorporate them.

The critical issue is to ensure that the method matches the task and the data. In addition, cartographers and others trying to visualize geospatial data will rely increasingly on multiple representations in multimedia environments where the linkages between displays of the same data in different forms need to be established and active. Similarly, we will employ technological means to combine different datasets (for example terrain data, sound data and navigational and gravity sensors) in the same display device.

Themes and issues summary

The themes and issues detailed above in five sections identify multiple 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 generalisation, organisation 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 (how representations can be accessed and enhanced).

Dramatic changes in technologies have led to changes in the forms of representation available to the spatial data handling and related information science and technology communities and the potential of these representation forms for productive use. The research agenda outlined in this paper, generated by the international cartographic community, can help address the issues raised by such developments and encourage a structured and focused response to this rapidly changing domain.

State of the Art

In order to address the general issues raised in the last section it is necessary to describe the contemporary nature of representation and its links with visualization and the role of both in mapping and cartography. Recent work in the discipline of cartography has expanded the range of representational methods and technologies available: an overview of current technology is central to a survey of representation possibilities. These new forms of representation all possess the elements that characterise cartographic visualization (interactivity, investigation of unknowns, private study). The implications of this expanded cartographic toolbox 'are inextricably related to the other issues addressed in this volume - interface design, cognitive research and other methodologies such as data mining, geo-computation 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.

This section does not, therefore, explicitly address the five central issues so far defined, although these are introduced and underlined as appropriate. Instead, there is a concentration on the map as a representation device and an overview of the current state of cartographic representations.

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 physical (and visible) and intangible phenomena, and to 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.

Maps have long been regarded by cartographic theorists as models (Board, 1967) and such a viewpoint led to the dominant paradigm of western cartography in the late twentieth century, characterizing the map as a communication model using abstraction, representation and design to convey a message to a community of users. From this perspective on cartography, the role of representation in mapping is as a means for communicating spatial data effectively and efficiently. Further, and ongoing, investigation has addressed the appropriateness of particular representations and the efficiency of those representations (Ogrissek, 1982; Freitag, 1993). Research over the past decade, however, has modified the paradigm (DiBiase, 1990; MacEachren, 1995) to consider broader issues, particularly those associated with how map-based displays enable creative thinking and problem solving (the results of which might then be communicated, also with a map-based display). Cartography and cartographic research are also being expanded by the new types of representation discussed above and are extending into new areas as we become able to usefully map new types of data.

The use of representations in scientific and geographical enquiry relies on the distillation and portrayal of data. Cartography has a central role to play in such data handling, whenever geospatial data are involved: it allows us to portray raw data, the graphical combination of disparate data sets, and 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 spatial 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

Beyond its role as a tool for representation, the map can often be seen as a metaphor for the presentation and representation of all types of data, spatial and non-spatial. Other metaphors exist by which spatial data handling can be characterised (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 summarised 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 2: at end of paper*), using terrain-like plotting methods. These spatialization methods have subsequently been applied to geoinformation contexts (Fabrikant, 2000). Also in the virtual world, the visualization and understanding of web connections in cyberspace has benefited from use of mapping tools (Dodge, 1999). Even within the spatial data handling community, features such as topographic slope and aspect and surface artifacts (borrowed from the physical landscape map metaphor) have been used in the mapping of other types of spatial data such as socio-economic variables (Wood et al., 1999).

The map metaphor is potentially broad in its derivation and application. Maps can be characterised by the degree of abstraction possible in the representation of geographic data (MacEachren and Ganter, 1990). 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 it 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 3*). 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.

Figure 3: Continuum of realism with Imhof and Chernoff representations (from Dykes et al., 1999)

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 contemporary tools, 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. The virtual reality (VR) that they offer, with both spatial and temporal realism, is becoming a standard cartographic method of performing representations of spatial data (Wheless et al., 1996). Representations within VR are attractive for concrete, complex, data-rich, real world phenomena such as landscapes, urban scenes and terrain (Bishop and Karadaglis, 1996). In such environments, contemporary VR can often require an intensity of representation, more concentrated than everyday nature - in effect, 'more real than real' (Gillings, 1997). However, we should note that, like a map, 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 (2000b) has listed further related aspects that affect map representations and the user's response and these can be profitably examined to determine the factors that should 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 study of the map as a metaphor for accessing spatial 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 spatial **data** we are handling changes, so the map representations which are used to visualize it changes also.

MacEachren et al. (1999) outline a useful classification of representation **form**, based on cartographic design practice, which refers to the 'iconicity' of the display. This is the extent to which display dimensions match the spatial dimensions of the world, and to a certain degree matches the continuum introduced above in the context of virtual reality displays. The realistic map is regarded as spatially iconic, creating a space-to-space mapping between the real world and the display. As MacEachren et al. point out this "does not require that virtual environments replicate reality (that they be representationally iconic in all respects) - any more than traditional maps need to look just like a view from above to take advantage of the space-to-space mapping in 2D". They further point out that whilst a realistic rendering of a tornado in three-dimensional VR might be visually compelling, enhancement may be necessary: "true insight (of the tornado) can only be gained when wind direction, speed, and temperature are represented through abstract visual symbology".

A more schematic representation results when non-spatial variables are incorporated into displays as one of the three spatial dimensions. When *time* is used, for example in some of Szego's perceptive visualizations (1987), as an integral part of the graphical display, considerable insight can result. Other non-spatial variables such as pressure and rock type are suggested by MacEachren et al. (op. cit.) as capable of display by Hovmuller plots, an example of semi-iconic representations which combine spatial and temporal dimensions in one graphic (*Figure 4*).

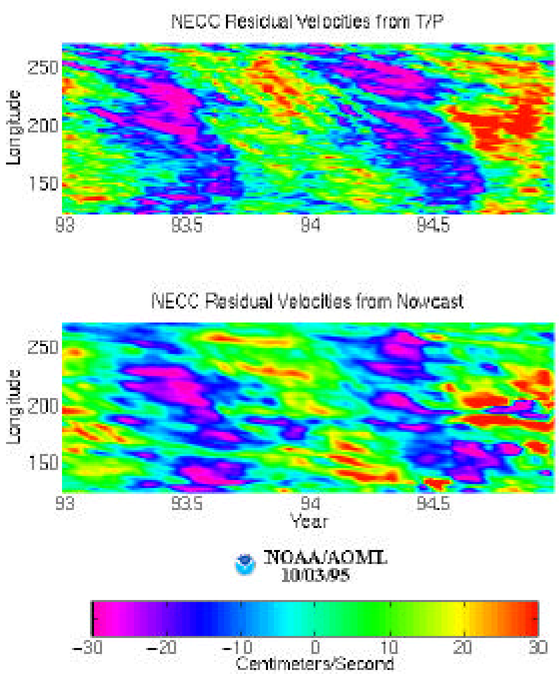

Figure 4: Hovmuller plot (from Harris et al., 1996)

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 some current visualization tools. Multi-dimensional scaling, for example, is possible using XGobi (Swayne et al., 1997); Dorling (1992) 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). They also consider the technological tools used for representation: it is clear that representation is distinct from but related to the *technological and interface possibilities* available. It can be suggested that technology enables new representations and new representational demands prompt technological advances. Thus, the introduction of dynamism, animation, interactivity and hyperlinking has led to new methods of data representation: 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. Work on dynamic map behaviors (Shepherd, 1995) can provide a foundation for such research. The output from other technological advances, such as head-mounted displays (HMDs) and CAVEs are already expanding the range of specific virtual environment and data representations that require investigation.

It is noteworthy that the categories of representation developed from this classification 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). As well as being influenced by technology and the user, representation is both data- and task-dependent, something long recognised by cartographers.

Schematic representations and EDA

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), and these have been applied and extended by cartographic researchers to develop representations of multivariate datasets. Work by Monmonier (1989), MacDougal (1992) and Dykes (1996) has led the way in opening up cartography to such possibilities. Monmonier's exploratory techniques link statistical and geographical views of data to great advantage, examining the nature of scatterplots and the information contained within them, for example. The graphical scripting methods, used by Dykes, demonstrate the direct links between representation and interface and explicitly document the cartography, dynamism and behaviors contained in maps for exploration. Edsall (1999) proposed an extension of brushing, termed 'strumming', as an interaction method for use with parallel coordinate plots that are dynamically linked to maps. The contemporary results of such work include accessible software such as cdv (Dykes, 1997, 1998), Descartes (Andrienko and Andrienko, 1997, 1999a) and GeoVISTA Studio (Gahegan et al., 2000) (*Figures 5* and *6*: *at end of paper*). Further work, both technical and conceptual is needed to extend and fully explore the range, consequences and suitability of these new, dynamic representations of geographic information. The techniques used by Dykes (op. cit.) and Andrienko and Andrienko (op. cit.) are especially suited to the evolving cartographic milieu, as their inherent flexibility (taking advantage of high-level scripts and Java libraries respectively) mean they are specifically extensible and can support rapid prototyping. GeoVISTA Studio is also a Java-based environment, providing a Java Beans-based visual programming to allow for easy combining of components written by users.

The importance of task-driven representation

The Themes and Issues section above stressed the importance of taking into account the map use and the map user when creating and interacting with representations. This section notes some further issues related to task-driven representation and the **purposes** for which representations are created. A perceived or actual community of users or the demands of an individual spatial data user drive the representations so far described, as true for all cartographic products. The representation of scientific hypotheses (for example, in sketch form), of scientific data (for example, in archiving and for communication purposes) and of scientific results (for example, in pictorial or graphical summary) is undertaken for a number of purposes and to meet the functional requirements of a number of tasks. The exploration of complete scientific datasets will require a different form of representation to the comparison of a couple of individual observations. The summarizing of a complete scientific investigation will be rendered in a different form to the highlighting of a dataset outlier. Summarizing, exploring, extracting, feature identification, feature comparison and feature interpretation (attaching meaning) are examples of tasks in scientific work, all of which can lead to various types of representation. Clearly, delineating the functions of representation, matching of representation type to differing tasks and assessing the appropriateness and efficiency of representations are as important, if not more so, than merely cataloguing the techniques that exist to create such representations.

Realistic data

The development of EDA techniques has led to an engagement of representation methods with statistical analysis. Multivariate data handling and multi-temporal analysis can be used to understand the opportunities and limitations already explored by scientists whose main aim is the handling of numerical, as opposed to spatial, data. A substantial research effort has also been directed towards the realistic representation of physical phenomena, rather than the more schematic representations mentioned above. (MacEachren et al., 1999). In creating such representations of the 'real world', researchers have used geovisualization along with knowledge of how human beings interact with and view their surroundings and the elements within 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. Beyond this, we can imagine a human being addressing and reacting to more than the visible characteristics of geographic environments: instead to "experience 'super environments' in which users can not only see what would be visible in the real world, but also experience the normally invisible and control what is usually beyond human control" (MacEachren et al., op. cit).

Technological possibilities

As indicated above, the map metaphor is well embedded in the mind-set 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. The development of these new data handling environments and **technologies** means that a re-assessment of cartographically familiar tools and parameters needs to be undertaken.

Color, for example, is an interesting tool and visual variable that has been subject to recent scrutiny within the new paradigm of cartographic visualization. Choropleth mapping is a central instrument of graphical exploratory data analysis of enumerated georeferenced statistics (for counties, nations, etc.), and color variation is the symbolization of choice for such displays. The detection of spatial pattern, regionalization and assessment of relative value are all spatial data analysis techniques that are enhanced by the portrayal of data through attributes of color. Brewer's research (1994), for example, has extended the overall view of color as a visual variable initially developed from a cartographic perspective by Robinson (1952) and in a wider graphic sense by Bertin (1967). Such work has resulted in the standard application of three color variables – hue, value and saturation – in the representation of different types of data (for example nominal or ordinal data). Broader examination of the role of color in geovisualization has been undertaken by Levkowitz (1991), Levkowitz et al. (1992) and Rheingans (1997). Further uses of color and the 'packing' of more information into color representation must be researched as opportunities and demands develop.

Another example of how technological development can stimulate modified and new representations is in the area of animation and dynamism. The wider range of visual variables inherent in such displays can allow for a more efficient allocation of variables to the spatial, symbolic and temporal dimensions. It may be possible to use temporal variables to represent non-temporal phenomena (Openshaw et al., 1994) and the semantics of such animations need examining. In addition, there are positive benefits in using multiple screens to address simultaneous change, and transparency and blending tools to address comparison within one display. The addition of visual navigation tools and temporal legends (Buziek, 2000a) can also ease the interpretation of animated and dynamic sequences.

Applications areas for new cartographic media are constantly widening. It is only recently that corporate business, for example, has appreciated the role of maps and map-like objects; it is only recently that spatial data has been incorporated into financial and insurance applications; it is only recently that the widespread availability of mapping over the Internet has led to high user expectation of map representations delivered by the web. It is only recently that we have been able to geo-locate ourselves with a high degree of accuracy using an affordable device that fits in the pocket (and that we need to re-acquaint ourselves with the limitations of mapping on the low resolution, monochrome LCD screen that such pocket devices use). As the realm of human endeavor to which spatial data can contribute expands, so *the range of representations and methods of portrayal widens and so the need to develop and test the most appropriate techniques continues.* The research challenges outlined in the next section therefore address both representational theory and the development and testing of techniques which are supported by such theory.

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 which best serve the requirements of contemporary spatial data handling. Some of the central research tasks we propose here have been introduced in the preceding sections 'Themes and Issues' and 'State of the Art'. Here we expand further upon the range of issues and structure our agenda in a more formal manner. We delineate challenges related to the five aspects of representation we have stressed already: 1) the methods and practices of representation that are affected by **data**; 2) conceptual issues in creating representations and the subsequent **form** of representation; 3) the tasks and **purpose** to which they are applied; 4) the interaction that is involved in accessing representations and the impact of the **user**; and 5) the tools and **technology** that are used in representation. The aim in promoting the research challenges is to attain successful understanding of each of these issues: 1) to fully appreciate how representation is affected by spatial data; 2) to be aware of the background issues relating to representation and its methods and develop a theory for formalizing these; 3) to know the possibilities, applications and limitations of representation; 4) to comprehend the nature of the human input into representations and the effect of representations on human beings; and 5) to be completely familiar with the range of technological opportunities available. Successful undertaking of the research agenda will deliver an expansion of conceptual and practical knowledge in this important area of spatial data handling.

The impact of data on representation

This section considers some research tasks in the area of the spatial data used to create representations, the inherent meaning of that 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 by the scientific community as a critical research issue (for example, 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, those generated by 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 further common characteristic of contemporary data is its dynamic nature. Clearly animated and vibrant forms of representation can adequately 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, evaluation of 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. Most of the critical problems relevant to science and society today for which geospatial data are fundamental, involve (as indicated above) change and process. Methods developed thus far to represent data, data interpretation, and decision uncertainty, however, do not consider change or process. Thus scientists and decision-makers are faced with analysis tools and decision-making aids that often ignore uncertainty entirely – leading to wasted scientific effort and bad decisions. 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. Further development of the visual variables exemplar for representation design has concentrated on matching the nature of the data portrayed with the representation displayed. Some work attempted to embed this into expert systems for cartographic design (Zhan and Buttenfield, 1995; Forrest, 1991; Muller and Wang, 1990). In addition, Mackinlay (1986) demonstrated the feasibility of using such technologies for representing non-spatial data. More recently created visualization software has offered intelligent graphical representation of data using metadata and a cartographic rule base (for example, Vizard (Jung, 1995); Descartes (Andrienko and Andrienko, 1997)), but such extensions into interactive display have revealed the shortcomings of previous expert system tools for map display. It is likely that, in addition to using dynamic visual variables, a further range of representation techniques needs to be developed specifically for interactivity. It is valuable to study map use strategies in this respect (Andrienko and Andrienko, 1999c): 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 be aware of the limitations of traditional cartographic methods and designs, 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.

- While past research has delineated the primitives (variables) of dynamic display, a major challenge for cartography is to produce a standardized approach to the use of such variables in contemporary dynamic and animated representations. Further, it is important to determine the nature of animation as a tool for exploratory analysis, beyond its straightforward display function. Shepherd (1995) suggested that "whenever dynamic features are added to maps [we should] ask the question WHY?" (p.184). Further research into the use of dynamic representations for visualization should be directed towards addressing this question and also explaining 'HOW?' and 'WHEN?' dynamic graphics can be used appropriately and successfully.

  As cartographers engaged in experimenting with *animations* we know that there are problems in viewing these 'as a whole' (Morrison et al., 2000). We still do not know what makes animated displays too complete, too busy, or too spatially and/or-temporally distracting (Shepherd, 1995). Often many re-runs of an animation sequence are necessary to pick up the full picture; users interacting with animated sequences are unable to view different portions of the display simultaneously; there are difficulties in locating a point in the temporal sequence with the same accuracy that a point in space on a static display can be remembered and moved to (Slocum et al., in press). 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 thinking clearly about the distinct roles played by temporal variations in map display we may identify conflicts and begin to address these issues. These behaviors provide a wide range of representational possibilities with evident benefits for visualization that can (and should) be dependent upon the user, their experience and preferences, and the task in hand, as well as the data, the medium used and the hardware configuration.

  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 (Blok et al, 1999). 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. This may be developed using novel techniques such as those afforded by the MPEG-7 format, which can be used to address *video* representations of data with spatio-temporal properties. Extracting information from video and exploiting interactive video requires new data models and interfaces and novel graphical representations. Video representations of properties, shoppers and vehicles will soon be interactive so that details about the objects in the video can be investigated.

- The application of 'non-conventional graphics' for representation covers a range of techniques which need further 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 (which can help in portraying change) and highly schematic or highly realistic representations (dependent on the data, the user and the task involved in representation) require fundamental research enquiry to determine their effectiveness. A focussed research program will help to assess their potential role as standard tools for the creation of maps.

- The specific issue of the desirable *level of realism* in varying cartographic representations is of immediate importance as spatial data (especially image data) becomes available at ever-higher levels of resolution and as the complementary need to abstract a simplified representation from complex data becomes apparent. Whilst recognizing that maps are abstractions of reality, rather than faithful reproductions of it, 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 interpreting spatial data than a highly detailed and complex virtual world. Examination of the tornado model by MacEachren et al. indicated that it may be preferable to show additional, abstract variables in generalized, rather than realistic form. An assessment of the relative benefits of using either realistic or schematic displays to represent a range of data, both tangible and non-visible, can help in the efficient use of cartographic representations.

Current methods used to display terrain data and contemporary practice in computer graphics and computer gaming can exhibit striking levels of realism: but the realistic rendering of terrain in virtual environments needs to be reconsidered. It is vital, in a cartographic context, to ensure that appropriate abstraction of detail is undertaken, ensuring that human interaction can proceed efficiently. Further, as we increasingly utilize technology which can merge the abstraction rendered by cartographers with the realism presented by computer graphics scientists we need to determine the relative levels of each for the task in hand.

- As is clear from the ability of individuals with visual impairment to interact independently with their environment, senses other than vision are capable of rapid processing of complex information. Still, 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 co-ordinate position, range and direction can be specified. Whilst preliminary 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: 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 (þsycho-acoustics þ; the role of conceptual and realistic sounds; and the incorporation of the human voice in spatial information systems. Each of these is a crucial issue in the development of effective visualization systems which utilize the richness of contemporary spatial data.

  Research into *sound* as a cartographic variable (either as an accentuating supplement to visual representation or as an independent means of encoding spatial data which is not depicted visually) is necessary. In which scenarios can sound be combined with other representations? How does the user react to sound? More fundamentally we need to determine how sound research is undertaken - how can we test the applications in which we suspect that sound may be valuable? (Shiffer, 1995). Some virtual worlds can be experienced with additional *haptic* (touch) *techniques*. This is an area of importance to cognitive scientists (Yokokohji et al., 1996) which can play a substantial role in some means of representation. The portrayal of stimuli using physical forces rendered through kinesthetic gloves or pressure-sensitive clothing is intimately connected in VR with navigation, balance and machine-response to user control. 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 it. Technology already exists to portray resistance in a tactile manner - which could be used to represent attractiveness, gravity models, or theoretical location-planning scenarios (for example, 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.

  As well as sound and sonification, further enhancement of traditional mapping within contemporary visualization systems can make use of voice interactivity and recognition along with natural gestures (Sharma et al., 1999). Expanded *multimedia interfaces* and their multi-sensory representations (visual, auditory, haptic) are now commonplace: once again the opportunities for and mechanisms of information representation and transfer to the user must be studied.

- We have established that distinct methods of representation exist on the abstraction continuum discussed above (*Figure 3*). 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*. Possible mechanisms for transferring data, edits and information between representations have not been explored thoroughly. 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. 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 spatial 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. As was indicated earlier in this section, cartography has borrowed and modified many of the graphical tools of exploratory data analysis, some of which (such as 'brushing') do allow for user interaction in one view that has simultaneous impact on linked objects/places in other views. At a human interface level, it is important to note that the capacity to respond to differing types of changes in differing representations may be limited. There may, for example, be conceptual problems involved in assessing the depth of the human understanding of the linkages displayed by brushing. Even existing issues such as the impact on the viewer of varying representations of the same object, 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 spatial data processing* operations can ease their interpretation and support effective and appropriate data application. This may extend to a method of 'programming' which involve symbols or widgets representing software and data components that are graphically connected. The graphics are converted into computer code or scripts and the processes run, with the interactions and operation visualized. Such graphics often permit feedback into the computational process and so visualization of its progress and outcomes. AVS, and IBM Data Explorer provide such representations, as does the ERDAS Imagine software where the Model Maker tool provides a visual approach to creating procedures for processing satellite imagery. Such visual methods can be further applied to processes of data querying and the development of spatial data models and structures. Our experience with these visual programming techniques indicates that relationships between them and cartographic visualization require further investigation. The key challenge here is to integrate geovisualization and these visual programming methods in ways that support understanding of complex geospatial data processing operations.

Tasks and applications – the purposes of representation

The issue of interaction with representations can be expanded to consider the relative appropriateness of various types of spatial data display. The fundamental question to be answered is 'what is a suitable method of representation for this particular task?' This area is particularly difficult to examine, relying, as it does, on unquantifiable factors such as an assessment of knowledge acquisition and the efficiency of data exploration. Cartographic and graphical representations, including those offered by EDA, can assist significantly in providing a framework for such exploration: the Descartes mapping tool, for example, can act as the spatial data display extension to a knowledge discovery device, Kepler (Andrienko and Andrienko, 1999b). It is difficult to answer the question of whether insight results from the individual expertise of the user or the effective rendering and use of visualization.

- The use of graphical editing tools into practical visualization tasks can be supplemented by also integrating the type of statistical tools used in EDA and data mining. These can clearly affect the method and look of visualization, although they are currently used mainly for static, two-dimensional representations. 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 data mining techniques for the initial exploration of graphical data.
- 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? '
- Although some recent experiments on the use of particular maps in some *spatial decision making* processes have not been particularly successful (Jankowski and Nyerges, 2000), it is expected that maps in general will still prove to be of significant use in such decision making. 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), for example, suggest that practitioners prefer univariate small multiples, rather than single multivariate maps – but the relative advantages and disadvantages of small multiples and composite views for different applications remains an important open research question. Multi-criteria analysis could benefit considerably from such displays (Carver, 1999), but clearly there is need to develop appropriate and task-specific representations. We contend here that interactive representations show most promise in this particular spatial 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 amplification also, military personnel in training, fire-fighters, mining engineers and utility workers 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. The more intangible representation would contrast with the 'real world 'viewed simultaneously, and thus further research is required to determine exactly what is required from these *superimposed portrayals.*

Users 'responses to representations and implications for interactivity

Whether accessed in multi- or single-user environments, representation can be enhanced with the incorporation of supplementary techniques.

- Multi-user environments are of importance for a variety of researchers and decision-makers who are engaged in group work. In practical terms, these environments could be useful for '*virtual workbenches*', as shown in *Figure 7*, (Ottoson, 1999) where mission critical handling of dynamic, three-dimensional spaces (for example for air traffic control) requires the input and participation of a number of users. Again, such constructs require investigation to determine effective methods of representation and interactivity to ensure efficient use of spatial data. A related issue is that virtually all past work on visual representation (whether the representations are static or dynamic, interactive and animated) has been directed to representations to be used by one individual at a time. A conceptual as well as practical approach is needed to develop representation forms explicitly designed to be shared.

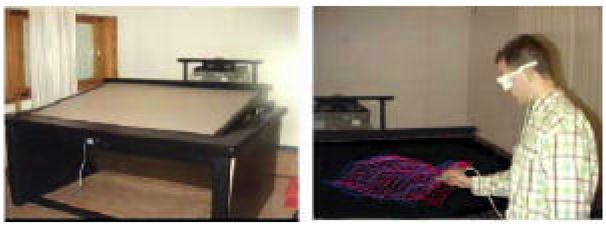

Figure 7: The Immersive Workbench and the observer with stereoscopic glasses, tracking system and stylus (the grid can be seen in stereo with anaglyph glasses) (from Ottoson, 1999)

- 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 and experience. The competence of users must be addressed and appropriate representations created for differing user communities. The role of visualization in air traffic control (as indicated above) 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 and interactions with, the representations presented.
- Facilitating *navigation* in complex geoinformation spaces represented by virtual environments and through virtual representations of datasets is a 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 visualization software: 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 themselves (Andrienko and Andrienko, 1999a) in response to user input; or automated methods of determining parameters for analysis could be invoked. This might extend to detecting and measuring eye-movement parameters or finding new ways of identifying, selecting or concentrating on data within a map. In effect, the interaction between the human user and the automated data mining tool needs to be more specifically examined in the context of graphical display. 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.

Tools and technology for representation

A range of display technology methods is already used for cartographic representation and embedded into visualization systems for handling spatial data. There is considerable scope, however, to further research into the representation methods which take advantage of new technologies, particularly those which make new kinds of representation possible (such as environments completely experienced through sound, tactile and kinaesthetic feedback, rather than merely visually).

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 such data can be presented to an outdoor user to supplement the real world ('*augmented reality*') or by which such data can surround a user's senses within the confines of a head-mounted display. 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 head mounted displays 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. Cartographic research has already been initiated in this area (Hardy, 2000).

- *Immersive environments* have been further developed recently, from the initial beginnings of 'video-walls,' giving large-scale 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?
- We have already discussed the conceptual nature of designing representations for shared use: the technology of such *multi-user environments* is also of importance. These methods of display, which can also be immersive, allow for social interaction and shared experiences. These 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 spatial context (for example, in environmental management or in city planning). Here, ideas can be discussed, opinions harmonized and solutions agreed. 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 of 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 subsequent decisions based upon those data? How do we represent the existence, actions, relationships and viewpoints of the each user in a group of collaborators most effectively?

Data formats and coding methods

- As has been indicated, 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 in addressing concerns in representing spatial data. Certainly, the format and scope of VRML has been positively developed by the GeoVRML group (Reddy et al., 1999). These techniques allow for the enhanced and detailed representation of data projected into three-dimensional views of geographic space within environments that respond at speed in real time. They act as natural interfaces to cartographic data beyond the two-dimensional static map.
- Research into the means of *rendering* such representations must address concepts that cartographic researchers have addressed in response to previous technological advances. Research focused on 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 rapidly 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: how should navigational aids and paths through immersive three-dimensional spaces be represented; 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?

- Web-initiated novel 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 spatial data (Bosak and Bray, 1999). Developing these specifications to contain methods for portraying and interacting with geospatial information for visualization should prove beneficial. Ultimately 'stylesheets' for visualization that encode knowledge about exploratory techniques for spatial 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

The volume in which this paper appears 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, exploring as it does the fundamental nature of cartographic display using new media. From the outset we have addressed the intrinsic links with the other areas considered. Initially, the structure and content of the spatial *databases* from which the representation is drawn, and computational methods applied to those data prior to or in concert with visualization, will clearly have an impact on the nature of the visualization process. Further, and implicit in the review of technology outlined above, the role of the user or viewer in perceiving the resultant representation is important. 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 a vital part of the display. Another paper in this volume addresses the impact of navigational control, user input and behavior when representations are supplemented (using whatever means) by feedback loops. Similarly, the representation of spatial data needs to be addressed within the wider context of the overall *interface* between system and user: for example, the visual programming paradigm demonstrates an evident and useful overlap between interface and representation. Means of conveying representations (by vision, sound or touch), methods of displaying extra information (such as legends and scale), and techniques of informing the user of interactivity possibilities, are all part of the design and implementation of an effective human interface.

Research work in all these areas depends on the production of prototypes that advance the field and allow for testing - of the expanding range of representation methods, of the technological tools used to portray representations within a cartographic system, and of the effectiveness of such representations for real-world applications and real-world users.

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 through which to approach proposed research work 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 it successfully. It may be possible to develop some rules (based on semantics and embedded as metadata) in order to ensure that the representations are valid, to enable their appropriate combination, and to avoid non-sensical displays that do not adequately reflect the data in the manner required for the completion of a particular task.

- Extending representations. We have identified considerable scope for using less obvious 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 intelligent databases, for example those that incorporate structures designed for display, navigation, streaming, mining or level of detail, and with novel data models, can be profitably considered.
- 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 spatial data handling tasks. This typology has two complementary roles. Firstly, it will provide a framework for developing new representation forms, by identifying data handling tasks that are currently not well supported, as well as a framework for comparing alternative representation forms empirically. Secondly, it will enable us to identify which representations are appropriate in which circumstances and match them to tasks (and user(s) and data), thus to develop systems that help users select appropriate representation forms to meet their needs and systems that 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 that are available, and the map behaviors that we can achieve will ensure the currency of cartographic products for visualization. Links to cognitive research issues may help to determine the levels of interactivity appropriate to certain tasks and users.
- 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.

The overall aim is to investigate and develop mechanisms that ensure that the representation is appropriate for the data, for the task, for the user, and for the technology.

We suggested at the start of this paper that there are new things to represent, that there are new methods of representation, and that there is 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 grounding of the discipline. This paper has examined the research avenues of most importance in addressing these issues. We have identified the critical research problems, examined the new representations, the technologies behind them and the nature of the representation process. In doing so we have revealed a range of outstanding research questions which need to be addressed. Some address 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. There is a clear need for significant investment of research effort in addressing these areas of concern. 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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Illustrations

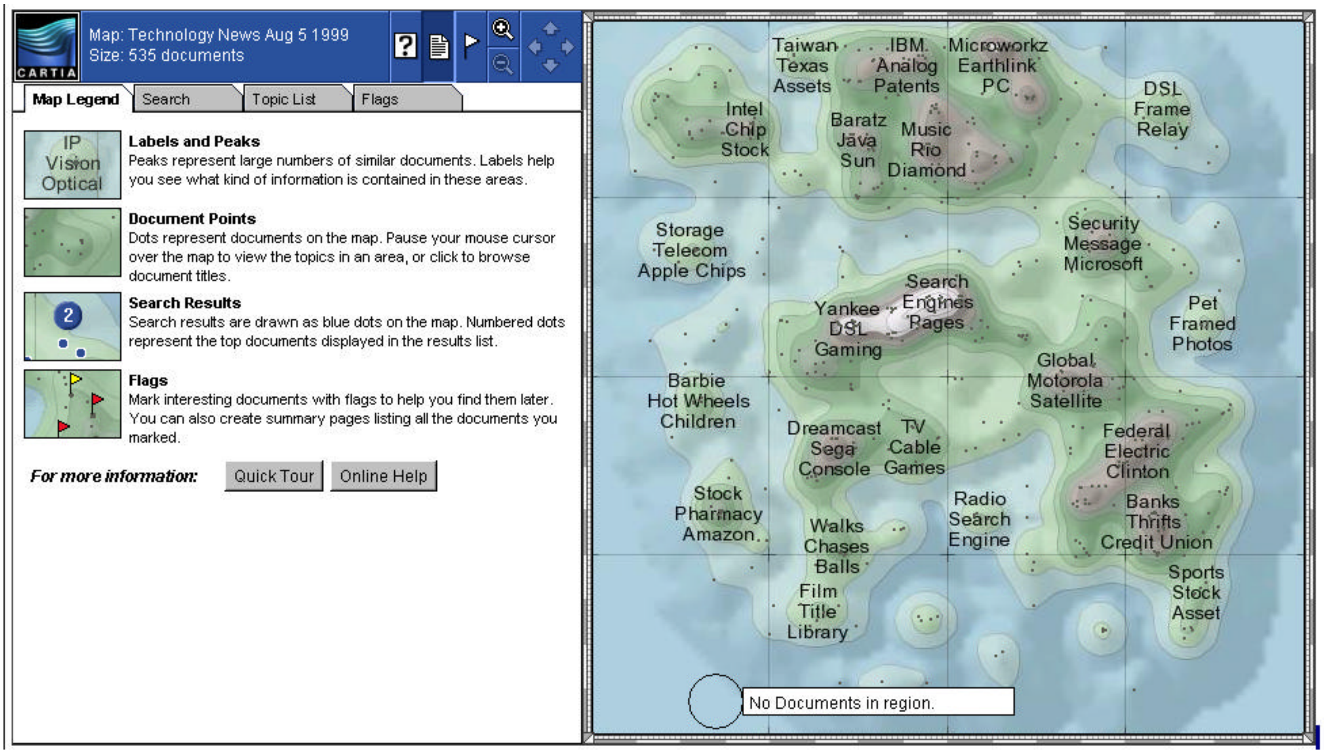

Figure 2: Themescape example

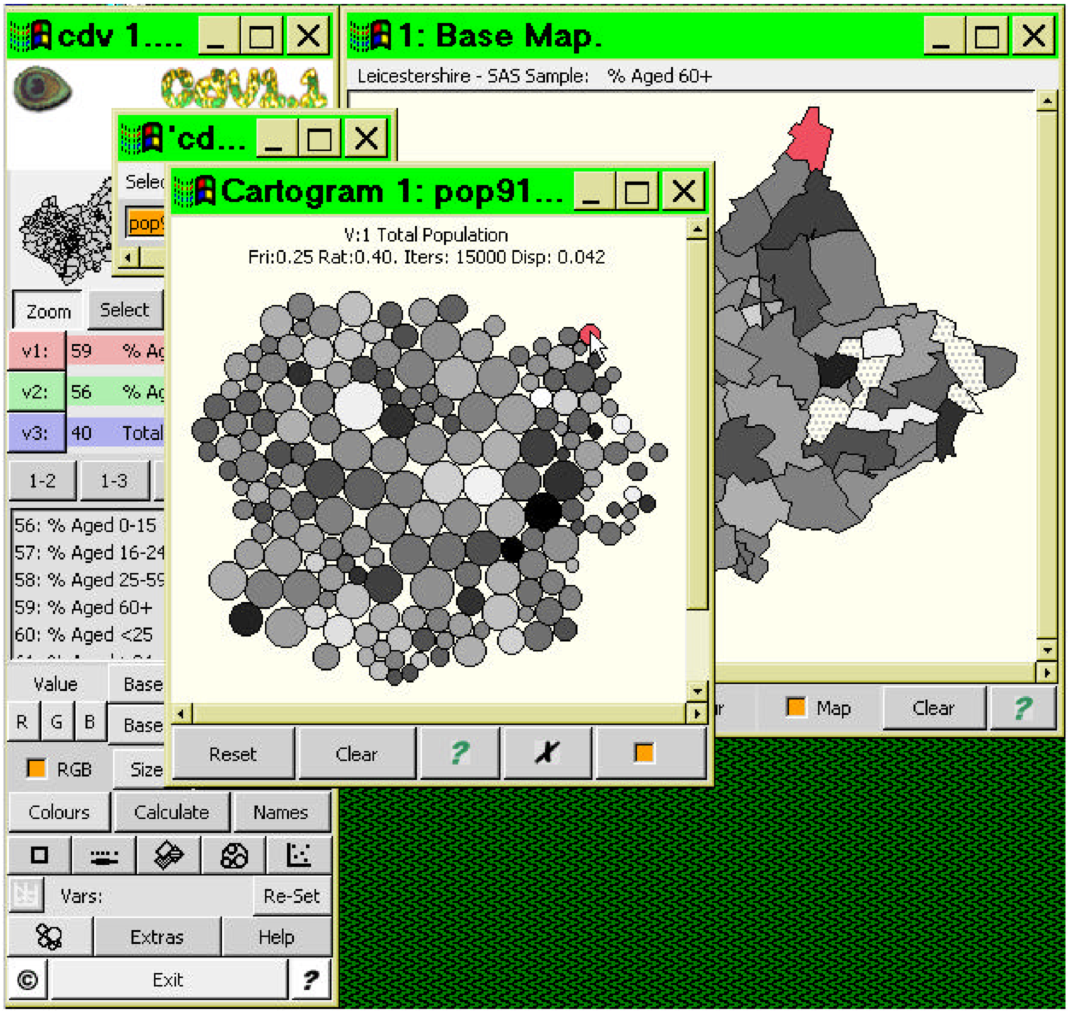

Figure 5: Screen shot of cdv (described in Dykes, 1997a)

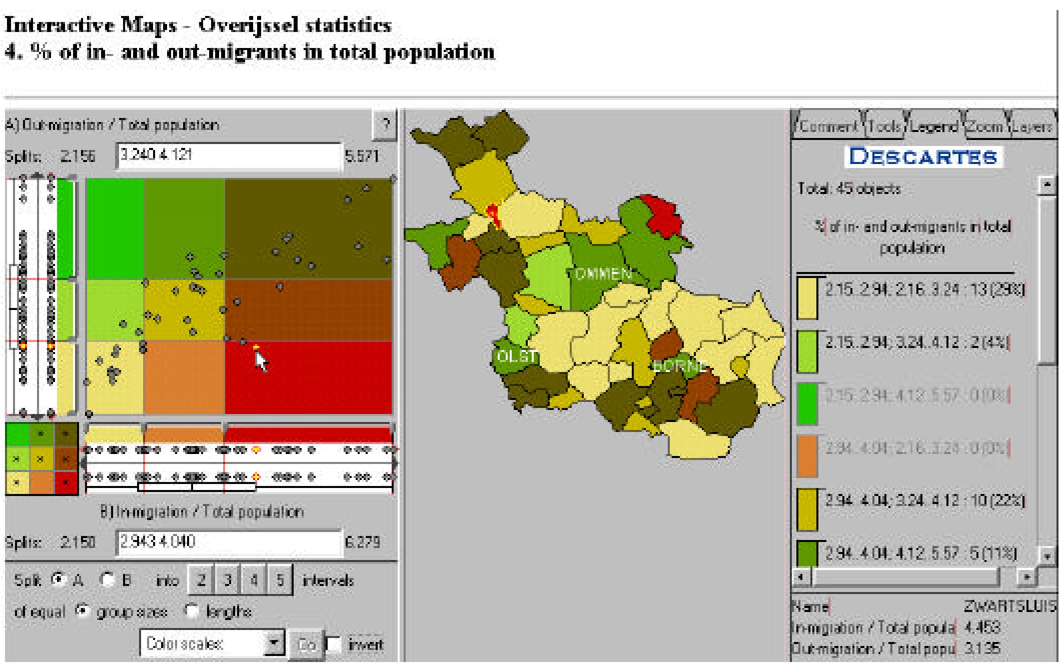

Figure 6: Screen shot of Descartes (described in Andrienko and Andrienko, 1999a)