Cognitive and Usability Issues in Geovisualization

Terry A. Slocum, Connie Blok, Bin Jiang, Alexandra Koussoulakou, Daniel R. Montello, Sven Fuhrmann, and Nicholas R. Hedley

ABSTRACT: We provide a research agenda for the International Cartographic Association's Commission on Visualization and Virtual Environment working group on Cognitive and Usability Issues in Geovisualization. Developments in hardware and software have led to (and will continue to stimulate) novel methods for visualizing geospatial data. It is our belief that these novel methods will be of little use if they are not developed within a theoretical cognitive framework and iteratively tested using usability engineering principles. We argue that cognitive and usability issues should be considered in the context of six major research themes: 1) geospatial virtual environments (GeoVEs), 2) dynamic representations (including animated and interactive maps), 3) metaphors and schemata in user interface design, 4) individual and group differences, 5) collaborative geovisualization, and 6) evaluating the effectiveness of geovisualization methods. A key point underlying our use of theoretical cognitive principles is that traditional cognitive theory for static 2D maps may not be applicable to interactive 3D immersive GeoVEs and dynamic representations – thus new cognitive theory may need to be developed. Usability engineering extends beyond the traditional cartographic practice of "user testing" by evaluating software effectiveness throughout a lifecycle (including design, development, and deployment). Applying usability engineering to geovisualization, however, may be problematic because of the novelty of geovisualization and the associated difficulty of defining the nature of users and their tasks. Tackling the research themes is likely to require an interdisciplinary effort involving geographic information scientists, cognitive scientists, usability engineers, computer scientists, and others.

KEYWORDS: Geospatial virtual environments, animated maps, interactive maps, metaphors, collaborative geovisualization, usability engineering, research agenda

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Introduction

The three previous papers in this issue of *CaGIS* propose research questions concerning representation, database-geocomputation-visualization links, and interface design that, once answered satisfactorily, promise a host of new methods for visualizing geospatial data.[1] Although the development of such methods is exciting, we argue that users may find these methods difficult to apply, not derive the full benefit from them, or simply not utilize them if we do not consider various *cognitive* and *usability* issues. To illustrate, imagine that we develop a tool to assist school children in visualizing how temperature changes in a lake over the course of the year. We develop the tool explicitly for an immersive geospatial virtual environment (immer-

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[1] Here, "methods" should be interpreted to include both the conceptual approach to a geovisualization problem and its implementation through specific tools.

sive GeoVE)[2] because we think that children will develop a better Afeel@ for spatiotemporal variations in temperature if they are immersed in the lake environment. Although hardware and software exists that could enable development of such a tool, we would have to make decisions on numerous cognitive/usability issues to insure the tool's success: for example, which immersive hardware (e.g., head-mounted display or CAVE)[3] would be appropriate for children *and* for this particular application; what sort of interface would be most appropriate for children; what representation (symbology) would be appropriate for depicting lake temperatures; and how might such decisions vary as a function of a child=s age, sex, culture, and other individual characteristics?

We argue that the development of effective geovisualization methods requires a two-pronged effort: theory-driven cognitive research and evaluation of methods via usability engineering principles. *Theory-driven cognitive research* (in a geospatial context) refers to studies that seek to understand how humans create and utilize mental representations of the Earth's environment, whether obtained via maps or by navigating through the environment (for example, by walking or driving an automobile). If we can develop theories of how humans create and utilize mental representations of the environment, then we can minimize the need for user testing of specific geovisualization methods. Examples of theory-driven cognitive research that direct attention to the role of maps and related displays in knowledge acquisition and use include the work of MacEachren (1995) and Lloyd (1997). Related work focuses on cognitive aspects of wayfinding (a term that is commonly used to describe our ability to determine and follow a path or route through the environment); examples include Gärling and Golledge (1993) and Golledge (1999).

Usability engineering is a term used to describe methods for analyzing and enhancing the usability of software (Dumas and Redish 1993; Nielsen 1993; Mayhew 1999).[4] Usability engineers are interested not only in whether software is easy to use, but whether it responds satisfactorily to the tasks that users expect of it. In cartography, the practices of "user testing" and "user studies" have much in common with those of usability engineering. It should be recognized, however, that usability engineering involves both *formative* and *summative evaluation*. Formative evaluation is an iterative process that takes place during software development, while summative evaluation is done near the end of software development (Nielsen 1993, 170).

There are several reasons why research funding is critical for studying cognitive and usability issues associated with geovisualization methods. First, and most practical, is that the hardware and software associated with novel methods is frequently expensive (a CAVE system can cost close to $1,000,000). If schools and government agencies are going to invest in expensive technology, they want to be sure that their funds are not wasted – that these systems truly provide advantages over traditional technologies. At the same time, we must recognize that the cost of creating GeoVEs is dropping (3D stereoscopic images can now be viewed for under $500 and low-end head tracking systems are available for under $1000; see http://www.stereo3d.com/sitemap.htm). If such technology becomes commonplace, we will need to know whether and how the technology can be effectively used for geovisualization. Second, novel geovisualization methods will require fundamentally different design approaches than existing methods; for example, creating a user interface for an immersive GeoVE is likely to be different than the traditional non-immersive desktop (CRT) environment. Third, a key feature of geovisualization methods is the capability to explore geospatial data (to uncover hidden patterns and relationships in space and/or time); such exploration requires a high degree of interactivity not characteristic of traditional software for spatial data processing. We need to

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[2] For our purposes, we define a VE as a computer-based representation that invokes a sense of realism. A GeoVE deals with virtual environments at a geographic scale as opposed to say, table-top or architectural scales.

[3] For an overview of hardware that produces a sense of immersion, see the May 1997 issue of *Computer Graphics*.

[4] Usability engineering presumes that developers utilize widely accepted principles of sound interface design, such as those described by Shneiderman (1998). The field of usability engineering involves more than computer-based products; for example, Dumas and Redish (1993, viii) "…consider the testing of a TV set with menus or an oscilloscope with software-based controls…"

determine appropriate methods for handling such interactivity and decide how these methods can best be integrated in a user interface.

In this paper, we consider six major research themes in association with cognitive and usability issues in geovisualization: 1) geospatial virtual environments (GeoVEs), 2) dynamic representations (including animated and interactive maps), 3) metaphors and schemata in user interface design, 4) individual and group differences, 5) collaborative geovisualization, and 6) evaluating the effectiveness of geovisualization methods.[5] In the next section of the paper, we introduce each of these themes and discuss the associated state of the art. In the following section, we present a set of research challenges for each theme that we believe must be tackled if geovisualization methods are to be used effectively.

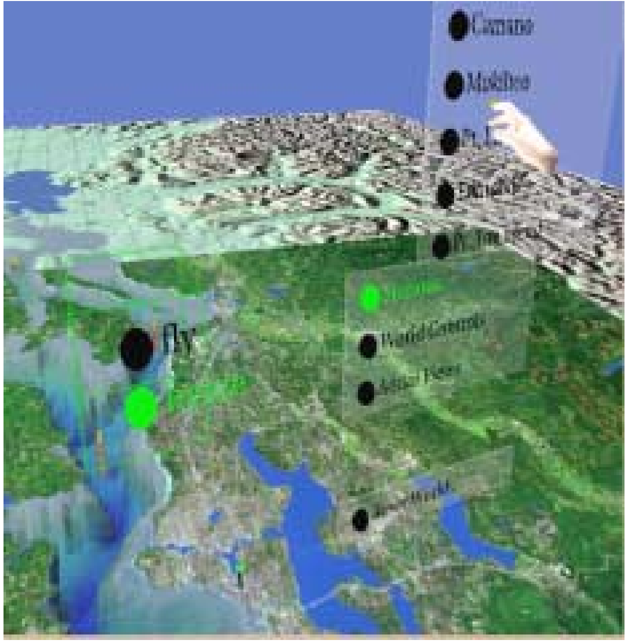

Figure 1. Virtual Puget Sound 2: an example of a GeoVE. Virtual Puget Sound 2 is an immersive GeoVE that presents coupled environmental models of bathymetry, Landsat imagery, three-dimensional water circulation, particle advection, and salinity. Users can move freely above the landscape and underwater using gestures. (Image courtesy of Nicholas R. Hedley, Human Interface Technology Laboratory.)

Research Themes and State of the Art

Geospatial Virtual Environments

It is logical to place GeoVEs first in our list of research themes because immersive GeoVEs fundamentally change our traditional way of acquiring spatial knowledge. In a desktop computer environment, maps generally have been depicted as an abstract 2D plan view (e.g., a choropleth map is viewed from directly overhead and represents data values through color or shading) and vision has been the primary means of acquiring spatial knowledge. In immersive GeoVEs, however, 3D representations are the norm (Figure 1), and it is possible to use a variety of senses: vision, sound, touch (haptic), and body (vestibular) movements. This new technology is exciting, but the cognitive-usability theory developed for representing geospatial information in a traditional 2D environment may not be applicable to this 3D, often more realistic, environment.

The notion of creating GeoVEs has blossomed in the 1990s. Within GIS, popular software packages now include realistic 3D mapping options (e.g., ArcView's 3D Analyst and ERDAS Imagine's Virtual GIS) and hundreds of packages have been developed solely for 3D mapping.[6] Publications related to 3D mapping have not been as prominent as new software, but we are beginning to see research results focused on the utilization and potential for 3D mapping (Kraak (1994), Hoinkes and Lange (1995), Buziek and Döllner (1999), Haeberling (1999), Hedley et al. (1999), and Patterson (1999)), particularly in urban applications (Day et al. (1994), Liggett and Jepson (1995), Doyle et al. (1998), and Batty et al. (1998b)).

GeoVEs can depict either the tangible or intangible world (e.g., a natural landscape or the average education of a population, respectively). Potentially, the greatest benefit of GeoVEs may be for depicting the intangible world because they allow us to look at the unseen in ways that we have not been able to with traditional 2D

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[5] Our research themes are based, in part, upon earlier work done by the ICA Commission on Visualization and Virtual Environments (see http://www.geovista.psu.edu/icavis/agenda2.html).

[6] A U.S. Army Corp of Engineers site (http://www.tec.army.mil/TD/tvd/survey/survey_toc.html) lists more than 350 packages purported to support "terrain visualization" alone.

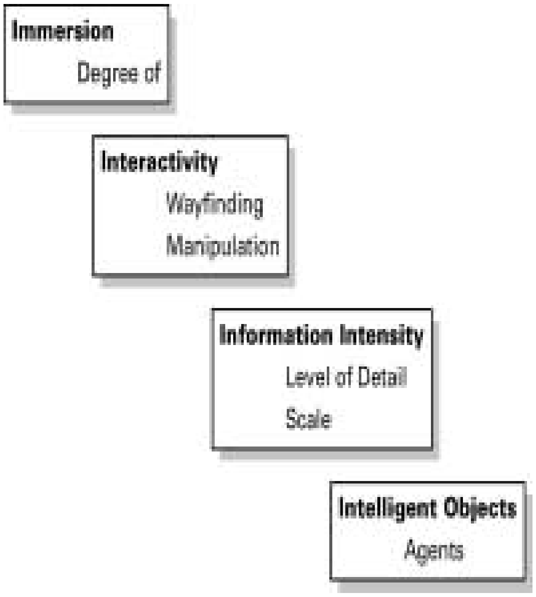

Figure 2. The four "I" factors important in creating GeoVEs: immersion, interactivity, information intensity, and intelligence of objects.

mapping (Bryson 1996; MacEachren et al. 1999b).[7]

Although software for creating GeoVEs has become readily available, the bulk of this software has been utilized in the traditional non-immersive desktop environment. This is starting to change, however, as researchers are beginning to report on the potential that immersive environments provide. Researchers in the GeoVISTA Center at Penn State University are among the most active groups exploring GeoVEs. Extending from the work of Heim (1998), they have proposed four "I" factors important in creating GeoVEs: *immersion*[8], *interactivity*, *information intensity*, and *intelligence of objects* (Figure 2) (MacEachren et al. 1999b). Since each of these factors signals a set of cognitive-usability issues, we will use them to summarize the state of the art in this section and to introduce research challenges in the subsequent section.

Immersion can be defined as "…a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment…" (Witmer and Singer 1998, 227). A traditional CRT display provides little sense of immersion, while a CAVE provides a strong sense of immersion. A reasonable hypothesis is that systems providing a greater sense of immersion will be most effective because: 1) they come closer to matching how we normally perceive the real world than do non-immersive systems (at least when depicting the tangible world), thus permitting us to use real-world cognitive processing strategies (Buziek and Döllner 1999), and 2) we are less likely to be distracted by the real world outside the hardware. A counter argument is that cartography is successful (it has been for centuries) precisely because the world is too complex to take in at once – we need abstraction and a separation between representations and ourselves to help us make sense out of it.

Within geography, Verbree et al. (1999) examined immersion in the context of the landscape planning process in the Netherlands, but they did not consider cognitive issues nor conduct any user testing. Outside geography, Pausch et al. (1997) and Ruddle et al.(1999) have compared head-mounted displays (HMDs) with CRT displays. Both studies found that those using HMDs performed better, but not necessarily in all aspects; for example, Ruddle et al. found that HMD users navigated through virtual buildings significantly faster, but that the length of paths taken was no shorter.

We are just beginning to tap the full potential of being immersed. Early VEs relied primarily on vision, but today's VEs are starting to utilize sound (Golledge et al. 1998), touch (Berkley et al. 1999; Berkley et al. 2000), hand gestures (Sharma et al. 2000), and body movements (Bakker et al. 1999).

One concern with *interactivity* (the second I factor) is developing methods to assist users in navigating and maintaining orientation in GeoVEs.[9] Rudolph Darken and his colleagues

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[7] For those wishing to create intangible VEs, specialized "visualization software" is frequently used, such as Data Explorer and AVS. For a list of visualization software, see http://www.prenhall.com/slocum/tools.htm; for an evaluation of such software, see Slocum et al. (1994) and Uhlenküken et al. (2000).

[8] Technically, we should distinguish immersion from *presence*; for a discussion of this issue, see Witmer and Singer (1998). A greater sense of immersion leads, typically, to greater presence.

[9] For our purposes, navigation is "the method of determining the direction of a familiar goal across unfamiliar terrain", while orientation is "concerned solely with direction and not destination." (Fuhrmann and MacEachren 1999) after (Baker 1981).

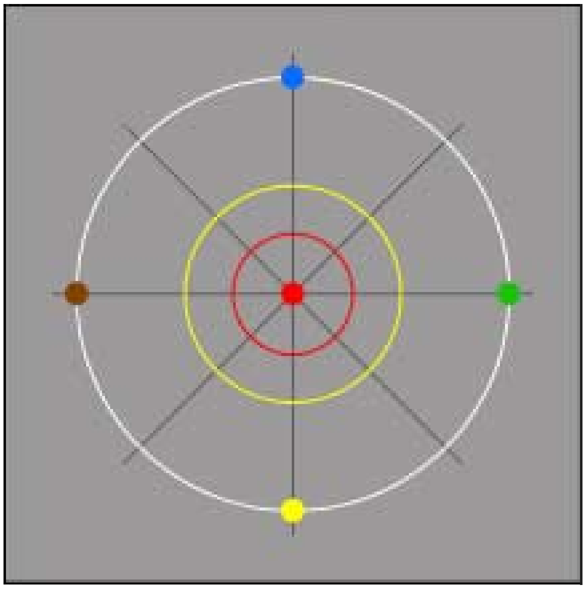

Figure 3. An example of how environmental design principles were applied by Darken and Sibert (1996) to assist users in navigating a large VE. This diagram was used to divide the VE into distinct small parts, provide spatial ordering (e.g., by color), and provide directional cues (each of the outermost points had a "flag" pointing toward the red innermost point). (After Darken and Sibert (1996, 56).)

have undertaken fundamental work on this topic. In one study, Darken and Sibert (1996) examined the ability of people to navigate very large GeoVEs (a hypothetical land-sea environment) and found that real world environmental design principles could be utilized in the GeoVE (Figure 3). Their work is relevant to our goals because they used cognitive theory to design their navigation system (e.g., the work of Thorndyke and Stasz (1980)) and usability engineering methods throughout design and implementation. In a subsequent study, Darken and Cevik (1999) examined how a virtual map might assist users in navigating a GeoVE, finding that different tasks were facilitated by different map types.[10]

In considering navigation and orientation issues in GeoVEs, there is considerable research on wayfinding that could be applicable. In fact, those interested in wayfinding have begun to recognize the potential that VEs provide for examining wayfinding issues (Péruch and Gaunet 1998), and some research has already been completed (Klatzky et al. (1998) and Richardson et al. (1999)).[11] Although such research is potentially applicable to geovisualization, it must be recognized that the purposes of geovisualization and wayfinding are different fundamentally. The objective of wayfinding research is to understand how people learn about and navigate through the environment. The primary goal is to find and move to a particular location. In contrast, the objective of geovisualization is to develop methods that will assist in understanding the Earth's environment. Here, the primary goals are to support searches for the unknown and the construction of knowledge.

Another concern related to interactivity is the extent to which users interact with and modify objects in a display. Presumably, users will require a set of interaction options similar to those found outside GeoVEs, such as brushing, focusing, and colormap manipulation (Buja et al. 1996; Dykes 1997). The three-dimensional realistic appearance of the environment, however, will allow a host of operations that we normally would not think of in two-dimensional maps, such as picking up objects and rotating them. Gabbard and Hix (1997) summarize numerous interaction techniques that have been attempted in VEs, while Bowman and Hodges (1999) present formalized methods for developing and analyzing such techniques.

Information intensity (the third I factor) deals with the level of detail in the GeoVE. Conventional rules for generalization as well as research advances in automated map generalization (e.g., the January 1999 issue of *CaGIS*) may be useful in deciding on the appropriate level of detail. The rules have, however, never been tested in GeoVEs and the research has been oriented toward abstract symbolization for 2D maps. Support for changes in detail as users zoom between scales is being tackled now (as part of the Digital Earth project -- http://www.digitalearth.gov/), but the approaches developed address the issue primarily from a technical standpoint (Reddy et al. 1999), without considering cognitive or usability issues. Level of detail is related to the notion of geographic

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[10] For recent research on cognitive factors that may influence navigation in VEs, see Cutmore et al.(2000).

[11] Chen and Stanney (1999) have developed a theoretical model of wayfinding that may assist in developing navigation strategies in VEs.

scale, a topic for which fundamental cognitive questions are only beginning to be explored (Montello and Golledge 1999).

Intelligent objects (the fourth I factor) raise some appealing possibilities for assisting users in interpreting GeoVEs. Outside the field of GIScience, *intelligent agents* (in the form of *avatars*) are being used to teach people how to work with machinery (Johnson et al. 1998; Rickel and Johnson 1999), for representing individuals handling a global crisis, and for advertising and presentation (Encarnação et al. 1997; Noll et al. 1999).[12] Borrowing from these examples, we can imagine agents assisting users in navigating through and understanding virtual geographic landscapes or in retrieving geospatial information (Cartwright 1999b).

Within geography, Michael Batty and his colleagues have used computational agents to model individual behavior in urban settings (Jiang 1999; Batty and Jiang 2000) and experimented with having users negotiate the same VE traversed by agents (Batty et al. 1998a). If users join agents within a VE, then there will be some important cognitive issues to consider -- does this, for example, facilitate learning about how crowds behave?[13]

One issue not explicitly dealt with in the four I's is the emerging technology of *augmented reality* (AR).[14] In most virtual environments, a virtual world *replaces* the real world, but in AR a virtual world *supplements* the real world with additional information (Feiner et al. 1997). For example, someone travelling in an urban environment might want to see building names overlaid on the actual buildings. A particularly promising aspect of AR is the potential for collaborative visualization (Billinghurst and Kato 1999).

A second issue in VEs not dealt with in the four I's is *health and safety hazards*. While it is unlikely that these hazards are specific to geospatial uses of VE, hazards ranging from tripping over a cord while immersed in a VE to *cybersickness* (a form of motion sickness that can result from exposure to VEs) should be taken into account. For work on such issues, see Stanney et al. (1998, 339-343) and Wann and Mon-Williams (1997, 55).

Dynamic Representations

We use the term *dynamic representations* to refer to displays that change continuously, either with or without user control. Dynamic representation has changed the way users obtain and interact with information across the full range of display technologies, from CAVES to traditional desktop computers. One form of dynamic representation is the *animated map*, in which a display changes continuously without the user necessarily having control over that change. An argument for utilizing animation is that it is natural for depicting temporal data because changes in real world time can be reflected by changes in display time. For instance, Figure 4 illustrates two frames from a classic animation of temporal data – Treinish's (1992) portrayal of the ozone hole. Animation can also be utilized for atemporal data; examples include fly-bys and sequencing data from low to high values.[15]

In addition to enabling animated maps, dynamic representations also permit users to explore geospatial data by interacting with mapped displays, a process sometimes referred to as *direct manipulation*. For example, in Figure 5 a user can explore the spatial pattern by moving a slider along the dot plot to adjust the midpoint of the diverging color scheme (Andrienko and Andrienko 1999). Those who have developed exploratory interactive software include Rheingans (1992), Dykes (1996; 1997), Shneiderman (1999), and Fishkin and Stone (1999).

Interactive exploration can also be considered in the context of animated maps. Although many animations have been developed with minimal opportunity for interaction (e.g., those distributed in video form), the greatest under-

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[12] Within geography, avatars have received relatively little interest, although Crampton (1999) proposed that they be used in a virtual campus map. It should be noted that the term avatar can be used to represent something inert as well as intelligent since the term is often used to refer to position markers for a person inside a virtual world.

[13] For additional information on the use of agents in geography, see Rodriques et al. (1998).

[14] AR is a subset of mixed reality (MR), which is a mix of virtual and real environments (Drascic and Milgram 1996). For a survey of AR issues, see Azuma (1997); perceptual issues in AR are discussed by Drascic and Milgram (1996)

[15] For an overview of how animation can be used, see DiBiase et al. (1992) and Slocum (1999).

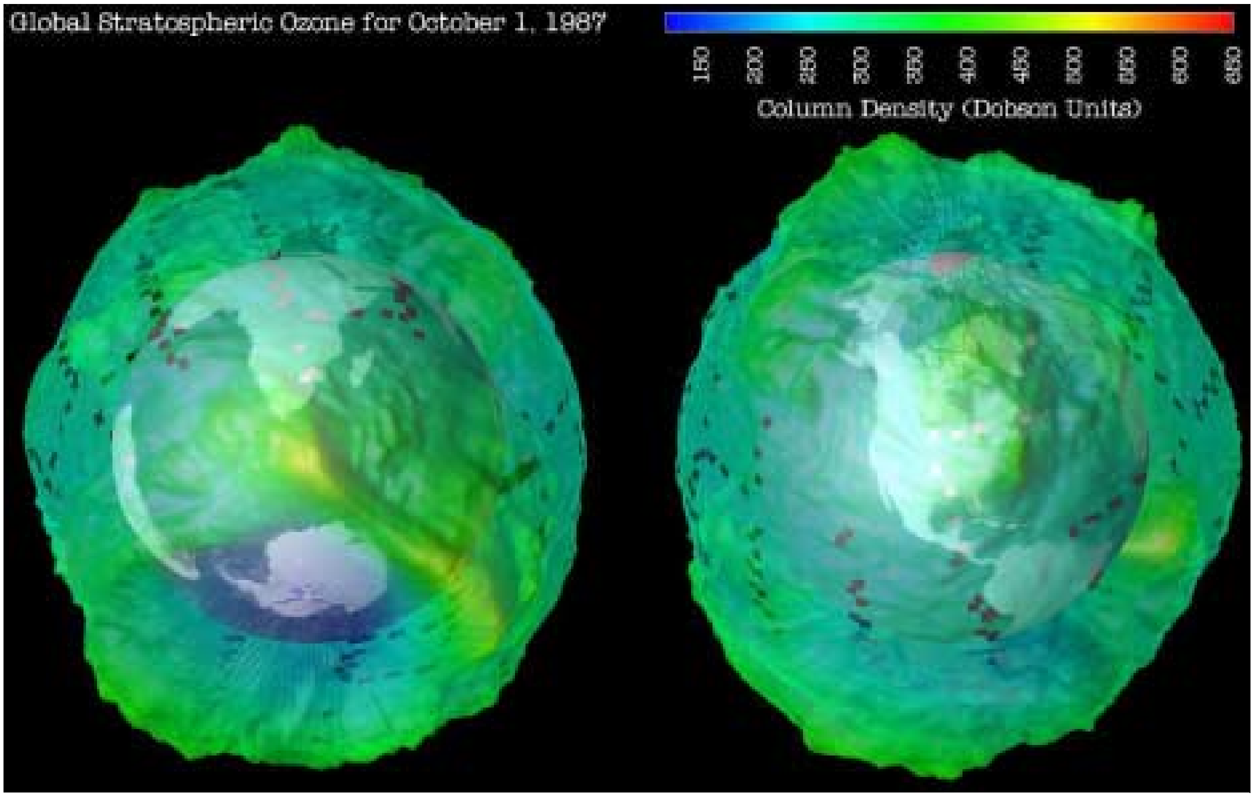

Figure 4. Two frames from an animation by Treinish (1992) portraying the ozone hole. A key research question is determining what information can be gleaned from static images such as these as opposed to an animation of the data (Courtesy of Lloyd Treinish, IBM Thomas J. Watson Research Center.)

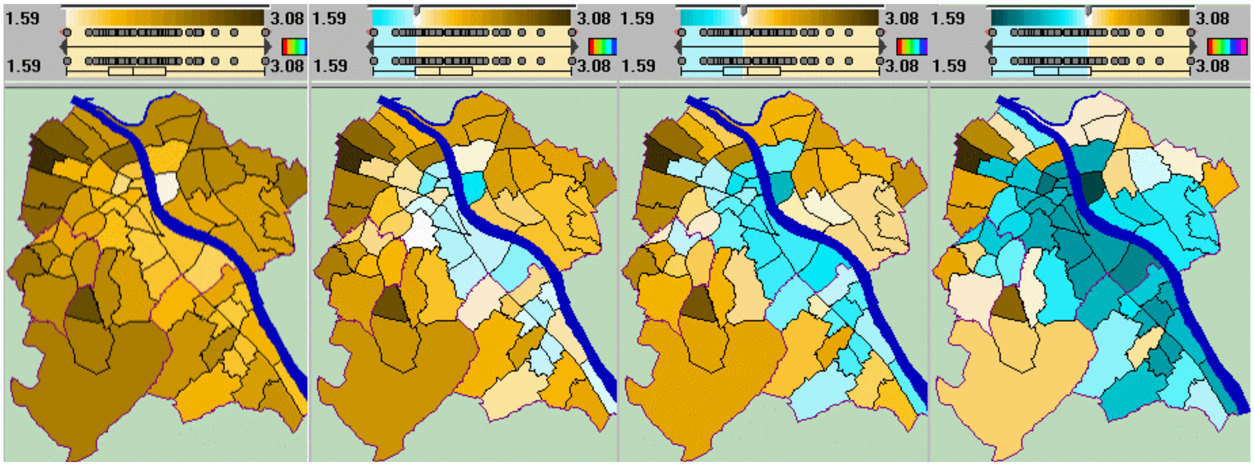

Figure 5. How spatial pattern can be analyzed by *interacting* with a map display. As the user moves a slider along the dot plot at the top of the figure, the spatial pattern appears to change dynamically. (From Andrienko and Andrienko (1999, 363); for information on the *International Journal of Geographical Information Science*, see http://www.tandf.co.uk.)

standing may be achieved when the animation is under complete user control and the geospatial data can be explored in a variety of other ways (Andrienko et al. 2000b; Andrienko et al. 2000a; Slocum et al. In press).

More generally, although the notions of animation, exploration, and interactivity have enticed cartographers, we should ask whether dynamic representations truly work. Do animations permit users to interpret spatiotemporal patterns more effectively than static maps and do interactive displays enhance user understanding of spatial patterns (Scaife and Rogers 1996)?

Studies of the effectiveness of animated versus static maps have produced mixed results. For example, Koussoulakou and Kraak(1992), Gershon (1992), and Patton and Cammack(1996) found that animation was more effective, while Slocum et al. (1990), Slocum and Egbert (1993), Cutler (1998), and Johnson and Nelson (1998) found little difference between animated and static maps.[16] Although in total these studies provide support for animation, a meta-analysis by Morrison et al. (2000) suggests that animations generally are *not* as effective as static graphics for educational purposes.

We need to consider Morrison et al's study carefully, since it contradicts the commonly held notion that animations can be effective, while recognizing that the animations used in studies they reviewed generally did not depict geospatial information. A key problem Morrison et al. pointed out was that a fair comparison between static and most animated graphics was not possible because static graphics were missing the microsteps shown in animations. This suggests that the display of microsteps might be the power of animations. From our perspective, one potential limitation of Morrison et al.'s methodology was their assumption that the effectiveness of animation must be evaluated in the absence of interactivity. It is our experience that animations are most effective when users have control and thus can interact with them (just as when users are free to control the attention paid to locations in a static graphic). Thus, we need to evaluate animations, both *with* and *without* interactivity in various problem contexts.

Numerous variables might affect the understanding of animations, including the method of representation (symbology), the method of interpolating frames, and the nature of the phenomenon animated. Rather than performing usability tests of these variables, researchers have focused on approaches for identifying the fundamental elements of map animation design and on creating animations (e.g., MacEachren (1995), Acevedo and Masuoka (1997) and Blok et al. (1999)).

There have been few usability studies dealing with interactive displays, and the focus has been on manipulating animations. Edsall et al. (1997) evaluated the effectiveness of various legend forms (clock-like versus slide bar) in understanding a weather map animation, finding no difference for simple retrieval and interpretation tasks. Harrower et al. (2000) found that the addition of temporal brushing and focusing to a standard animation was not particularly effective for students, although those with moderate knowledge of the application domain benefited the most. MacEachren et al. (1998), in contrast, reported that when expert epidemiologists were provided tools that allowed them to focus on high death rate values during an animation, the experts detected space-time patterns missed entirely by those using the tools in other ways. Slocum et al. (2000) examined user preferences for animation, small multiples, and change maps in MapTime, a package for exploring spatiotemporal data associated with point locations. They found that people liked animation because it provided an intuitive sense of time and showed overall patterns well, a raw small multiple because one time element could be compared with another, and a small multiple composed of change maps because it focused on *changes* at particular locations.[17]

Metaphors, Schemata & Interface Design

When working with GeoVEs, dynamic representations, or geovisualization generally, a critical issue is the nature of the user interface. From our perspective, a key element of interface design is the metaphors used. The classic example of an interface metaphor is the "desktop metaphor", developed by researchers at Xerox, popularized by Apple, and now common in most operating systems. In theory, metaphors should work because a source domain can be "mapped" into the target domain (Lakoff and Johnson

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[16] We have focused on user studies of animation; others (notably Dorling (1992)) have made useful contributions regarding the effectiveness of animation without performing user testing.

[17] The Varenius Project of the NCGIA recently identified "Cognition of dynamic phenomena and their representations" as a "high priority" research topic (Mark et al. 1999). The results of a Workshop associated with this Project can be found at http://www.ncgia.ucsb.edu/Publications/Varenius_Reports/Cognitive_Models.pdf.

1980; Johnson 1987); for example, in the desktop metaphor, elements found in an office serve as the source domain. Although the desktop metaphor has been popular, many other metaphors are possible; for example, Kuhn (1992) cites the following as metaphors attempted in GIS: program, manipulate, communicate, delegate, query, browse, skim, produce and receive documents, solve problems, play, cooperate, see, view, and experience.[18]

Closely associated with metaphors is the notion of cognitive schemata (Neisser 1976). Ideally, interpretation using geovisualization will be enhanced if the form of representation and associated interaction match intuitively with schemata for structuring spatial information; for instance, providing a legend to a contour map that depicts the contours as irregularly shaped nested lines should prompt an appropriate schemata for interpreting map terrain (DeLucia and Hiller 1982).

Researchers have implemented metaphors potentially relevant to geovisualization in three domains: GIS, geovisualization itself, and information visualization.

In the context of *GIS*, Egenhofer and Richards (1993) and Elvins and Jain (1998) implemented a map-overlay metaphor (modeled on traditional overlays on a light table). Goodchild (1999) has proposed the Earth as a metaphor in association with the Digital Earth project (http://digitalearth.gsfc.nasa.gov/). Others who have worked with metaphors in GIS include Neves et al. (1997), Schenkelaars and Egenhofer (1997), and Blaser et al. (2000).

In the context of *geovisualization*, Kraak et al. (1997) and Edsall et al. (1997) utilized metaphors in developing legends for an animated weather map. Their notion was that clocks and timelines serve as metaphors for linear and cyclic components of time and thus should prompt appropriate schemata. Fuhrmann and MacEachren (1999) proposed the intriguing notion of a "flying saucer" metaphor for navigating 3D VRML desktop-based environments. Cartwright (1999b; 1999a; 2000) suggested numerous metaphors (e.g., storyteller, navigator, guide, and sage) that might be utilized to build a GeoExploratorium, a means for accessing a wide variety of spatial resources relevant to a particular geographical area of interest. Other metaphors utilized in geovisualization include Pang and Wittenbrink (1997) and Fishkin's (1999) spray-can and Magic Lens filter, respectively.

Metaphors relevant to geospatial information also have been used in *information visualization*, a burgeoning discipline with a focus on the visual representation and analysis of non-numerical abstract information (Card et al. 1999). The process of converting abstract non-numerical information into a viewable spatial framework has been termed *spatialization* (a term that signals parallels with cartography and geovisualization). Metaphors are relevant in this context in the sense that the resulting space will be most meaningful if users can relate it to their real world experience with geographic (and cartographic) space – a principle at the heart of work on applications such as ThemeRiver™ and ThemeView™ developed by information visualization researchers at Pacific Northwest National Laboratory (http://multimedia.pnl.gov:2080/infoviz/). Geographers working in information visualization include Kuhn (1997), Skupin and Buttenfield (1996), Couclelis (1998), and Fabrikant (2000).[19]

To date, most metaphors have been implemented within a Windows-Icons-Menus-Pointer (WIMP) interface. In contrast, Robertson et al. (1999) have developed a novel workspace interface that utilizes 3D perspective and animation. Also exemplary of the move away from WIMP interfaces is the work on *multimodal* and *natural* interfaces that attempt to mimic the way people interact with one another (for example, using gesture and speech). Oviatt and Cohen (2000, 47) note that multimodal interfaces are particularly effective for "…applications that involve visual-spatial information" (p. 47) (see Oviatt (1997) and Sharma et al. (2000) for examples).

Immersive GeoVEs have the potential for implementing relatively direct metaphors (at least for tangible phenomena), since the intention is to create a target domain (the VE) that has the "look and feel" of the source domain (the real world). For example, when sitting in the cockpit of a flight simulator, one is supposed to obtain the feel that one is actually flying. Im-

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[18] For more on interface metaphors, see the Cartwright et al. paper in this issue.

[19] For recent research on the usability of information visualization tools, see the November 2000 (Vol. 53, No. 5) issue of the *International Journal of Human-Computer Studies*.

plementing metaphors in GeoVEs is challenging, however, because of the varied specialized interaction devices that have been developed (Youngblut et al. 1996; Buxton and Fitzmaurice 1998; Buxton 2000).[20]

Individual and Group Differences

In considering research themes to this point, we have treated users of geovisualization methods as a homogeneous group. Obviously, this is inappropriate, as numerous variables could affect a person=s ability to work with a method, such as their expertise, culture, sex, age, sensory disabilities, education, ethnicity, physiology and anatomy, and socioeconomic status. Collectively, we refer to these variables as "individual and group differences." An important concern is what to do if we find that certain individuals or groups work more effectively with a method or with selected features of that method. We see two possible solutions. One is to train (or educate) people in geovisualization methods; the other is to design methods so they can be adjusted to the cognitive characteristics of the individual user.

In reviewing the state of the art related to individual and group differences, we will focus on five factors that could covary with cognitive differences among individuals: expertise, culture, sex, age, and sensory disabilities. The notion of *expertise* is complicated because it can be defined in so many different ways (Nyerges 1993; 1995). For our purposes, we will define expertise on the basis of three dimensions of user experience: with the tool, the problem domain, and computers in general (Nielsen 1993, 43-44). To date, an analysis of the role of expertise in geovisualization has been limited to two studies: McGuinness (1994) and Evans (1997).

Two aspects of *culture* need to be understood and incorporated into the design of geovisualization methods. The first is the need to translate linguistic information that is part of a geovisualization method. This is not as straightforward as it may seem, given that different languages label parts of the world in different ways that are only partially overlapping (for example, the meaning of "lake" vs. "pond" in English and French (Mark 1993)). A second issue concerns the interpretation of iconic symbols by different cultural groups. Iconic symbols are effective because they resemble what they stand for, making them easy to interpret (e.g., use of an airplane symbol to represent an airport). However, iconic symbols derive their semantics from people's experience, some of which is culturally specific; for example, the color *green* may suggest water more effectively than *blue* does in some cultures, and a cross is not universally a good symbol for religious institutions. Issues of the semantics of iconic symbols extend to auditory symbols as well -- what is "naturally" suggested by a particular sound (do low tones represent large features or objects)?

Sex has frequently been a variable examined in studies of traditional static maps (Gilmartin and Patton 1984). In the case of CRT displays, girls and boys do not use computer technologies in exactly the same ways, and thus different interface designs may be better suited for each (Jakobsdóttir et al. 1994). Males and females also have been shown to perform differently at "dynamic spatial reasoning tasks" such as the apprehension of the relative speeds of moving targets on a computer screen (Law et al. 1993). This may have implications for the way animations are used and understood by the two sexes.

Age is obviously a variable that can have considerable impact on our ability to understand visualization methods. It would be unusual to find a system that worked equally well with children and adults of all ages, which suggests the need for research on how best to design systems for use in schools and in public places where they will be accessed by children as well as adults (Liben and Downs 1992). Similarly, declines in spatial visualization abilities in middle and late adulthood have been documented (Salthouse and Mitchell 1990); and so their implications for geovisualization need to be investigated.

Sensory disabilities can also have considerable impact on success of geovisualization methods. Potential visual impairments include color blindness, low vision, and total blindness itself. Olson and Brewer (1997) developed color schemes to assist color deficient readers, but these schemes have not been tested in an interactive visualization environment, which has a limited color space compared to print media. Similarly, studies of map reading for those with low vision and the totally blind have been undertaken (Ungar et al. 1997; Blades et al. 1999), but not in the context of geovisualization. Other

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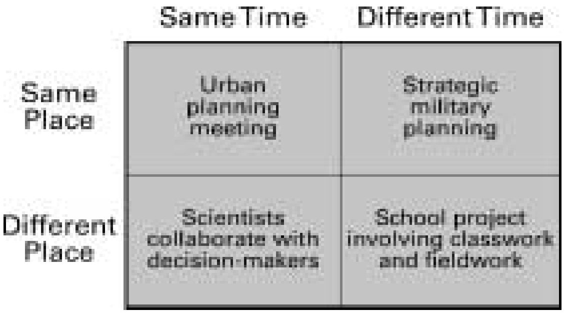
[20] For an example of a study involving metaphors in an immersive VE, see Peterson et al. (1998).



	Same Time	Different Time
Same Place	Urban planning meeting	Strategic military planning
Different Place	Scientists collaborate with decision-makers	School project involving classwork and fieldwork

Figure 6. Four different ways in which collaborative geovisualization can take place. The different place-same time scenario is particularly problematic because rapid communication may have to take place.

sensory and motor disabilities, such as deafness, have implications for how multi-sensory geovisualizations may be apprehended. For example, data *sonification* will clearly not work well with deaf users, but haptic methods might. Similarly, the field of spatialized sound (recreating 3D environments with 3D sound) is evolving (Loomis et al. 1990; Begault 1994; Loomis et al. 1998a; Loomis et al. 1998b).

In identifying the above factors as being associated with cognitive differences in geovisualization, it is important to remember that the factors should not necessarily be equated with the *cause* of a difference among individuals (Montello et al. 1999). Two people who speak different languages may have different cognitions because of something other than their languages, for instance, males and females may differ in their cognition because of some experiential variable that covaries with sex but is not determined by it. In many cases, it is beyond the scope of the geovisualization community to determine the ultimate causes for group differences, nor may it be important that we know these causes as long as we can identify reliable and consistent patterns of variation.

Since GeoVEs are one of our major research themes, it is important to consider individual differences associated with VE. In this context, Stanney et al. (1998, 332-334) note that attention to individual differences has been limited to sense of presence and cybersickness. Some of the areas Stanney et al. cite as needing work include assisting low-spatial users in maintaining spatial orientation, the difficulty that some individuals may have in handling multisensory input, differences in personality traits, and the role that age differences may play (e.g., the diminution of eye sight with age).

Collaborative Geovisualization

It is commonly assumed that individuals utilize geovisualization methods in isolation, but this is often untrue. For example, in a typical classroom situation, students may cluster around a computer monitor and freely exchange ideas about what they are looking at. With the availability of the Internet, *collaborative geovisualization* now can also take place over great distances and in fundamentally different ways (Bajaj and Cutchin 1999; MacEachren et al. 1999a). Designing visualization methods for such a setting is more complex for we cannot fine-tune the system for an individual, but must consider how the group of individuals will respond and interact with one another. Thus, both cognitive and social issues may be important.

The notion of collaborative geovisualization has its roots in Computer Supported Collaborative Work (CSCW) (Shum et al. 1997) and Collaborative Spatial Decision-Making (CSDM) (Densham et al. 1995). A variety of collaborative visualization efforts have taken place outside GIScience. Wood et al. (1997) and Bajaj and Cutchin (1999) have tackled many of the technical issues (e.g., enabling a collaborator to join and leave a session at any time). Shiffer (1995; 1998) has been a leader in implementing collaborative decision-making in planning, and is one of the few to have attempted a user evaluation of collaborative geospatial systems.[21] Complementary work includes Johnson et al.(1999) and the CoVis Project (http://www.covis.nwu.edu/) in education, and Rinner (1999) in planning. MacEachren (2000; 2001) reviews such work and its potential connections to collaborative geovisualization.

One point stressed by those involved in collaborative work is that collaboration can take place in four different ways: same place-same time, same place-different time, different place-same time, and different place-different time (Figure 6). Different place-same time geovisualization is particularly challenging because direct

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[21] Other work that may form a basis for evaluating collaborative systems includes that of Nyerges et al. (1998) and Reitsma (1996).

manipulation must take place remotely. Within GIScience, researchers at Penn State and Old Dominion University have experimented with different place-same time visualization of relationships between climate and topography utilizing Internet 2 and ImmersaDesks (MacEachren et al. 1999a), while a group at the University of Washington has developed a shared virtual space for remote synchronous and asynchronous geoscientific collaboration (Hedley and Campbell 1998).[22]

Brewer et al. (2000) are developing software that will enable both same-time/same-place or same-time/different place cooperative work by scientists working on problems related to environmental change. Following along the lines we promote in this paper, they are taking a human-centered design approach that involves iterative application of usability engineering methods.

Within immersive GeoVEs, collaboration is especially complicated because hardware limitations may prevent or limit the ability of individual collaborators to either see what others perceive, see what others are doing, or to make modifications in a shared scene. Particularly problematic are traditional HMDs, which generally have been used only by individuals in a non-collaborative environment; this is why geographers have become interested in table-top GeoVEs and the CAVE (Verbree et al. 1999). Even with these later systems, however, there is usually a single correct viewpoint and one person controlling the display. More flexible systems are possible that permit more than one controlling collaborator, with each person seeing a “correct” view (McDowall and Bolas 1997; Fuhrmann et al. 1998; Billinghurst and Kato 1999). These systems, however, have not yet been widely adopted, and they raise a variety of social as well as cognitive questions about how both control and the multiple perspectives generated might be shared.

Evaluating the Effectiveness of Geovisualization Methods

Our sixth theme, evaluating the effectiveness of geovisualization methods can be divided into two subthemes: 1) methodology for evaluating geovisualization methods and 2) practical utility of geovisualization methods.

Developing a Methodology

While cartography has a long history of perceptual-cognitive research on use of maps, experimental paradigms used were developed for studying static map use and the focus has been on comparing relatively narrow alternatives (e.g., a set of possible color schemes) for a narrow range of tasks (e.g., value retrieval or region comparison). Comprehensive usability evaluation throughout the lifecycle of map products has been uncommon.

One of the keys in conducting a usability study is specifying the users and the tasks that they need to perform (Mayhew 1999, 6-7). As geovisualization applications expand from their early focus on facilitating scientific investigation by experts to a broader range of users and uses, assessing usability becomes more complex. The standard usability engineering practice of observing potential users working with current tools provides limited (and sometimes misleading) insight on what they might do with geovisualization (because there is often no analogous situation using current tools to the kinds of data exploration that dynamic geovisualization can enable).

Cartographers have conducted a number of studies on the effectiveness of geovisualization methods, but these studies generally have dealt with just a limited portion of the software design-testing process, applying one or two techniques, rather than the broad range of methods that a comprehensive usability engineering approach requires.[23] Examples of methods utilized by cartographers include focus groups (Egbert 1994; Monmonier and Gluck 1994; Kessler 1999; Harrower et al. 2000); interviews (Slocum et al. 2000); and verbal protocols (MacEachren et al. 1998).[24]

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[22] Armstrong and Densham (1995) undertook some early collaborative cartographic work, but they did not emphasize the interactivity that we typically expect with geovisualization methods. For collaborative work in the context of GIS, see Churcher and Churcher(1999).

[23] For an overview of methods, see http://www.cs.umd.edu/~zzj/UsabilityHome.html.

[24] For an overview of qualitative approaches used in

Buttenfield (1999) is one cartographer who has looked at usability engineering from a somewhat broader perspective. In working with the Alexandria Digital Library Project (which did not involve geovisualization), she stressed the need to evaluate throughout the lifecycle of design, development, and deployment. Buttenfield also promoted a *convergent methods* paradigm in which multiple methods of evaluation are used (e.g., transaction logs, verbal protocols, and entry and exit surveys). In a similar vein, outside the field of geography Bowman and Hodges (1999, 43) have proposed a *testbed* of multiple methods for evaluating interaction techniques in VEs.

An important characteristic of how usability studies are conducted is the timing of software development and associated user testing. In this context, Gabbard et al. (1999) have developed an appealing methodology for evaluating VEs that might be applied to geovisualization methods (i.e., not just to GeoVEs).[25] The methodology is based on usability engineering and user-centered design (Norman and Draper 1986) and consists of four major steps: an analysis of user tasks (these are used as a basis for developing the initial software), an evaluation of the software by experts, a formative user-centered evaluation (in which users work with the software), and a task-based comparison of alternative implementations.

Practical Utility of Geovisualization Methods

Although we may develop geovisualization methods that are intended to “work” (for individuals or groups), we argue that such methods will be of little use if they do not actually enhance science, decision-making, and education outside the research laboratories where they are developed. Thus, we need to examine the effectiveness of geovisualization methods, both in the traditional laboratory setting (where they are developed) and in the “real world” (where they are actually used). To a certain extent, this research theme can be subsumed under the notion of usability engineering – as one of its fundamental stages is an evaluation of the software in real world practice (for example, Mayhew (1999) terms this the “installation” stage). We envision, however, that an examination of social issues related to the use of geovisualization in real world practice will extend beyond what usability engineers normally deal with.

Literature on user acceptance of information technology (IT) (Dillon and Morris 1996) falls within the framework of potential social issues that we might consider. Research on societal issues involved in GIScience is also potentially relevant to the utilization of geovisualization methods. A major portion of the Varenius Project of the NCGIA is dedicated to social issues, although thus far they have not focused on geovisualization (Sheppard et al. 1999). Finally, we may also wish to consider sociology of scientific knowledge (SSK) theory. One generally accepted tenet of SSK theory is that scientific developments do not occur in isolation from society, but rather are a function of the milieu in which they are developed (Barnes et al. 1996; Kourany 1998).

To determine the extent to which geovisualization methods appear to have facilitated science, decision-making, and education, we undertook a literature review. Using keyword searches of several bibliographic databases and our own knowledge of the literature, we found 71 applications that appeared to facilitate science, decision-making, or education (A summary is shown in Table 1; for a more detailed list, see Appendix A). Our intention was not to develop a comprehensive list, but to acquire a basic sense of how geovisualization has been

A. Science *Human Geography - 12* *Physical Geography – 18*
B. Decision making *Human Geography - 22* *Physical Geography – 9*
C. Education *Human Geography – 3* *Physical Geography - 7*

Table 1. Applications of geovisualization that appear to facilitate science, decision making, and education

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cartographic research, see Suchan and Brewer (2000).

[25] For details on their usability guidelines for VEs, see Gabbard and Hix (1997).

utilized. Not included in Table 1 are works in which the emphasis was on the development of geovisualization methods, as opposed to their application.

Although Table 1 suggests that geovisualization is being used to facilitate science and decision-making, one deficiency we noted was the lack of formal measures of success – the evidence is primarily anecdotal. With the exception of papers by MacEachren et al. (1998) and Shiffer (1995), published reports provide only indirect evidence that users benefited from geovisualization.[26]

In contrast to the common use of geovisualization in science and decision-making, Table 1 indicates a lack of geovisualization applications in education. In primary and secondary schools, this deficiency can be explained by limited funding, lack of training in geovisualization for teachers, the difficulty of fitting new material into an already full curriculum, lack of emphasis on new technology, and the traditional weakness of geography in the public schools (at least in the United States).[27] We can also argue that educators are reluctant to adopt this new technology quickly because we know so little about the ways in which children's developing spatial abilities can be enabled through visual representations – thus fundamental cognitive research is required to provide the basis for making critical decisions about use of scarce resources. Presumably, many of the above problems will dissipate as funds for information technology (IT) increase, teachers become better trained, and geography is promoted in the public schools. Certainly, children are ripe for geovisualization applications given their experience with place- and map-based computer and video games.

Research has begun to address some of the issues related to geovisualization in learning. Recent and current projects include Visualizing Earth (http://visearth.ucsd.edu/), KanCRN (http://kancrn.org/; the emphasis here is GIS, for which geovisualization could be considered a component), the Round Earth Project (Johnson et al. 1999) and the WorldWatcher Project (http://www.worldwatcher.nwu.edu/index.html).[28] In Canada and Sweden, school children are making use of electronic atlases associated with the national atlases of those countries (Siekierska and Williams 1997; Wastenson and Arnberg 1997). At the university level, visualization is now common in introductory geography courses, particularly those directed to the physical science components of the field, as textbooks typically include CDROMs containing visualization material.

Research Challenges

These are exciting times for those interested in the visualization of geospatial information. Development of visualization methods that use animated and interactive maps, multimodal interfaces, and GeoVEs (and associated AR) all have the potential to support insight into the vast array of spatial data that are now becoming available. To return to our school child example, we can imagine students not only examining temperatures within a particular lake, but being able to travel to various locations around the world and explore spatial problems at those locations, or see what it is like to live in a particular city (for example, it is now possible to take a virtual tour of portions of the Los Angeles metropolitan area – http://www.ust.ucla.edu/ustweb/ust.html). Although such potential is exciting, a great deal of time and money will need to be invested in order to develop effective hardware, software, and associated databases. We believe that these funds will be wasted if we do not consider cognitive and usability issues – the most sophisticated technology will be of little use if people cannot utilize it effectively. It is in this context that we see the following major research challenges related to cognitive and usability issues:

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[26] The Shiffer study was also unusual in that it was done within the workplace. Davies and Medyckyj-Scott (1996) and Davies (1998) have studied the use of GIS in the workplace, but their work was broad-based in that it did not focus on the effectiveness of specific pieces of software nor did it consider visualization.

[27] A number of these factors are discussed by Meyer et al. (1999, 571) in the context of GIS.

[28] The Human Interface Technology Laboratory at the University of Washington has long been known for its work in VEs with school children (Winn 1993; Furness et al. 1997; Osberg et al. 1997). For other work, see Roussos et al. (1999), the Virtual Reality and Education Laboratory at East Carolina University (http://soe.eastnet.ecu.edu/vr/vrel.htm) and The CoVis Project (http://www.covis.nwu.edu/).

Geospatial Virtual Environments

Determine the situations in which (and how) immersive technologies can assist users in understanding geospatial environments.

A related challenge is comparing the effectiveness of immersive technologies with traditional non-immersive displays. Given the variety of means that are now becoming available for simulating a VE (e.g., sound, touch, hand gestures, and body movements), this research effort will likely require multiple years by multidisciplinary teams of researchers.

Develop methods to assist users in navigating and maintaining orientation in GeoVEs.

This challenge is closely tied with research on interface design and metaphors, as users will need to interact with a display and navigate using suitable metaphors. A related issue will be determining the role that two-dimensional (bird's eye view) maps play in assisting in navigation and orientation.

Develop suitable methods for interacting with objects in the GeoVE.

Although these methods may be similar to those found outside VEs, the realistic 3D nature of GeoVEs suggests that a host of new methods will need to be developed. Since the precise nature of methods likely will be a function of particular applications, it will be critical to quiz potential users to determine what their needs are.

Determine ways in which intelligent agents can assist users in understanding GeoVEs

Intelligent agents that interact directly with users are likely to be useful because of the complexity of both information depicted and forms of representation used in the GeoVE. We anticipate that agents could be especially useful in educational applications.

Determine ways in which we can mix realism and abstraction in representations to influence cognitive processes involved in knowledge construction.

This challenge is driven by the focus of geovisualization on integrating diverse forms of information ranging from visible-tangible data about landscapes to non-visible and abstract data (e.g., ozone or commodity flows).

Developing support for interpreting and understanding spatial trends and patterns in GeoVEs.

As with navigation and orientation, this issue is challenging because users of GeoVEs may not have the birds-eye view that we are so familiar with in 2D mapping. Related research questions include whether novices could be trained to utilize schemata that share key aspects with those of experts, and whether agents can be trained by experts to explore on their own and/or to act as guides for less expert analysts.

Dynamic Representations

Determine the relative advantages of animated and static maps.

We anticipate that animation will be more effective than static maps in some situations; we need to specify those situations: in terms of which representations (symbology) are effective, the nature and degree of user control needed, the nature (complexity) of the phenomena being animated, how frames are interpolated, and what the problem context and specific tasks are.

For temporal animations, a critical concern is associating a proper time with various points in the animation.

Temporal animations are often difficult to understand because it is hard (with a rapidly changing display) to keep track of the match between display time and real world time. This problem might be tackled through multimodal interfaces (for example, using sound to signify position in time so that vision is free to observe changes in the phenomenon depicted).

Determine the appropriate mix of cartographic, graphic, statistical, and geocomputational approaches necessary for understanding geospatial data and how this mix varies with the application.

Animated maps are only one approach for understanding geospatial data. Effective geovisualization environments are likely to be ones that mix methods, but at this point we know little about effective user strategies for working with such integrated environments, nor how to design such environments to make them usable.

Analyze approaches to exploring geospatial data interactively in non-immersive desktop environments.

Here we refer to direct manipulation of parameters for interacting with spatial data (e.g., changing the portion of a spatial data set that is focused on). We specify "non-immersive desktop environments" to emphasize that there are still many unknowns in using this technology. Although interaction may be accomplished using standard WIMP interfaces, we should also evaluate the potential of multimodal interfaces.

Metaphors and Schemata in Interface Design

The overarching research challenge is to develop metaphors that make geovisualization methods more effective.

This will involve analyzing metaphors in existing software, considering past suggestions for metaphors (that may not have been implemented), and developing new metaphors. With multimodal interfaces, new metaphors are possible, and the potential exists to create more realistic metaphors (so-called natural interfaces are possible). In addition to developing appropriate metaphors, we also need to uncover the nature of the schemata people utilize in working with metaphors.

Individual and Group Differences

Develop methods to train (or educate) people in the usage of geovisualization methods.

In a sense, this is nothing new, as training has often been required to understand traditional static presentations (e.g., USGS topographical maps). With geovisualization methods, however, training will be necessary with both the method and the subject domain for which the method is intended (route planning, weather prediction, etc.). We anticipate that the strategies of experts in the domain and method could be studied and implemented in training approaches. The training itself might be carried out via the method; for instance, the method could prompt novices to use expert strategies.

Design geovisualization methods so that they can be adjusted to the cognitive characteristics of individual users.

This is the motivation behind the design of systems that incorporate Auser profiles@, descriptions of preferred ways to produce visualizations and interfaces that fit the cognitive characteristics of particular users. Some key questions related to user profiles include: What is the best way to design and implement them? How effective are they? Do users like them? Which aspects of a geovisualization method should be addressed by the profile?

Collaborative Geovisualization

Analyze cognitive and usability issues related to the overall design of collaborative interfaces, giving particular attention to ways in which shared task performance and thinking can be facilitated.

Although researchers have developed user interfaces that support collaboration, the focus has been on the technical challenges of building something that worked, as opposed to considering cognitive and usability issues. On a more detailed level, we need to examine group work tasks to determine which require geovisualization methods and tools that are different from those developed to support individual work. Also, attention should be given to the difficult questions concerning design of geovisualization that enables group work on ill-defined tasks such as decision-making and knowledge construction.

Analyze the many variables that can affect collaborative geovisualization within immersive GeoVEs.

Collaborative geovisualization and immersive GeoVE are both novel concepts. As a result, there are numerous variables that need to be evaluated for different problem contexts and kinds of group work tasks. These variables include: 1) the type of immersive hardware; 2) the number of collaborators and the kinds of control protocols; 3) the mix of non-collaborative and collaborative views; 4) how collaborators can interact with and appear to one another, and 5) visual methods for facilitating sharing of ideas and perspectives.

Evaluating the Effectiveness of Geovisualization Methods

Develop a methodology suitable for examining the effectiveness of geovisualization methods.

Although usability engineering provides a set of general guidelines for examining the effectiveness of computer environments, the focus of geovisualization on facilitating work related to ill-structured problems may make it difficult to apply standard usability engineering principles.

The key problem is that a clear specification of tasks (and sometimes of users) is often not possible due to the exploratory and interactive nature of geovisualization. Thus, we propose that cartographers, cognitive scientists, usability engineers, and others should collaborate to develop an appropriate methodology for examining the effectiveness of geovisualization methods.

Determine to what extent (and how) geovisualization methods facilitate science and decision-making in real world practice.

Although those writing about geovisualization methods contend that the methods facilitate science and decision-making, there has been little empirical evidence to support these claims. We propose extensive testing of geovisualization methods, both in the controlled setting of the research laboratory and in the real world. Usability engineering methods will be useful in this process, but we likely will also have to consider social factors beyond those normally dealt with in usability engineering.

Carefully examine the role that geovisualization might play in education.

In contrast to science and decision-making, we found few published reports of the practical use of geovisualization methods in education. This is unfortunate as geovisualization tools (particularly GeoVEs) have a dual potential for education. First, they provide new ways to facilitate understanding of complex spatial phenomena; for example, the realism of GeoVEs may provide ways to overcome difficulties that young children have in dealing with concepts such as scale or "stand for" relationships (e.g., that a flat map stands for a round world). Second, GeoVEs have the potential to support research in children's spatial cognition that is difficult or impossible to do in the real world.

Summary

We have outlined a set of research themes and associated challenges that we believe must be tackled if novel geovisualization methods are to provide useful knowledge concerning geospatial patterns and processes. The keys to our approach are the utilization of theory-driven cognitive research and the iterative application of usability engineering principles. Theory-driven cognitive research provides the basis from which a framework for designing methods can be developed. Usability engineering principles will be critical in insuring that applications are both easy to use and meet their intended tasks; additionally the iterative design process should assist us in developing cognitive theory.

Many of our research challenges focus on cognitive-usability issues associated with immersive GeoVEs, as we see VE to be a technology with considerable potential for extending the power of geovisualization. While immersive GeoVEs are intriguing, we also see that research is still necessary in more traditional desktop environments – thus our emphasis on dynamic representations as a separate research theme. The user interface is the key to utilizing any software, and so we have emphasized the study of associated metaphors and schemata, which should lead to more usable software. Research on individual and group differences is critical if geovisualization software is to be widely used. Collaborative visualization, like GeoVEs, is a recent development with many unknowns. It is a particularly important topic for research because the Internet and mobile computing both promise to extend the potential for collaborative work dramatically.

The complexity of challenges delineated requires a multifaceted approach, drawing upon methods from both cognitive science and usability engineering principles. It appears that if we are to examine problems such as group work with geovisualization and use of geovisualization in real world practice, we will also need to address social issues using methods that integrate perspectives from domains such as CSCW, sociology, and social psychology.

A common thread running through our major research themes is the need for interdisciplinary work. Oviatt and Cohen (2000) make the same contention from the perspective of computer science. They state

> "*Advancing the state-of-the-art of multimodal systems will require multidisciplinary expertise in a variety of areas beyond computer science – including speech and hearing science, perception and vision, linguistics, psychology, signal processing, pattern recognition, and statistics…To evolve successfully as a field, it means that computer science will need to become broader and more synthetic in its worldview, and to begin encouraging and rewarding researchers who successfully reach across the*

boundaries of their narrowly defined fields" (p. 52).

In tackling the research challenges we have identified, we believe that geographic information scientists should adopt a similar strategy – we can not hope to undertake these research challenges on our own, but will need to collaborate with cognitive scientists, usability engineers, computer scientists, and others.

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Appendix A. Detailed list of applications of geovisualization that appear to facilitate science, decision making, and education.

A. Science

Human Geography

agriculture - (Cox 1990)
archaeology - (Koussoulakou and Stylianidis 1999)
criminology - (Openshaw et al. 1993)
epidemiology - (Eddy and Mockus 1994), (MacEachren et al. 1998)
miscellaneous - (DiBiase et al. 1992), (Dorling 1992), (DiBiase 1994), (Krygier 1994)
transportation - (Eskafi et al. 1995)
urbanization - (Batty and Howes 1996; Buchanan and Acevedo 1996)

Physical Geography

atmospheric science - (Treinish 1992), (Koussoulakou 1994)
ecology - (Kreuseler 2000)
climatology - (Weber and Buttenfield 1993), (Howard 1995)
biogeography - (Buttenfield and Weber 1994)
environmental data - (Rhyne et al. 1993)
geology - (Painter et al. 1996), (Lin and Loftin 1998), (Bishop et al. 1999)
landscape processes - (Mitas et al. 1997)
limnology - (Assel et al. 1994)
marine geodesy - (Li and Saxena 1993)
meteorology - (Wilhelmson et al. 1990), (Hibbard et al. 1994), (Treinish 1995), (Treinish 1999)
miscellaneous - (Pang and Wittenbrink 1997)
oceanography - (Manley and Tallet 1990), (Manley et al. 1992), (Schrimpf et al. 1994),
(Howard and MacEachren 1996), (Wheless et al. 1996),
(Lindstrom et al. 1997)
soils - (Moran and Vézina 1993)

B. Decision making

Human Geography

coastal zone management - (Romão et al. 1999)
environmental planning - (Selman et al. 1991), (Lange 1994), (Levy 1995),
(Hebert and Argence 1996), (Moreno-Sánchez et al. 1997)
environmental studies - (Fonseca et al. 1999)
landscape planning - (Hoinkes and Lange 1995)
military planning and training - (Koller et al. 1995), (Schrader 1999)
nuclear fuel cleanup - (Hedley et al. 1999)
telecommunications - (Koutsofios et al. 1999)
transportation - (Ervin 1992), (Ottoson 1999), (Shiffer 1999)
urban planning - (Hall 1993), (Day 1994), (Bragdon et al. 1995),
(Liggett and Jepson 1995), (Shiffer 1995), (Ledbetter 1999)
water management - (Caquard 1999)

Physical Geography

disposal of radioactive waste - (Flinn 1998)
forest management and planning - (Orland 1994), (Uusitalo et al. 1997), (McGaughey 1998)
mining - (Russ and Wetherelt 1999), (Zack 1999)
natural resources management - (Bishop and Karadaglis 1997)
water resources planning - (Fedra 1993)
wildfire modeling - (Ahrens et al. 1997)

C. Education

Human Geography

history - (Miller 1988)
miscellaneous - (Dykes et al. 1999), (Winn et al. 1999)

Physical Geography

climatology - (Gordin et al. 1995), (Edelson et al. 1999)
ecology - (Orland et al. 1997)
miscellaneous - (Gordin and Pea 1995), (Krygier et al. 1997), (DiBiase 1999),
shape of the earth - (Johnson et al. 1999)