

Research Article

Developing a conceptual framework for visually-enabled geocollaboration

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Abstract. Most work with geospatial data, whether for scientific analysis, urban and environmental planning, or business decision making is carried out by groups. In contrast, geographic information technologies have been built and assessed only for use by individuals. In this paper we argue that, to support collaboration with geospatial information, specific attention must be given to tools that mediate understanding and support negotiation among participants. In addition, we contend that visual representations have a particularly important role to play as mediators of geocollaborative activities. With these contentions as a starting point, we present a framework for study of visually-enabled collaboration with geospatial information and for development, implementation, and assessment of geoinformation technologies that support that collaboration. The paper concludes with a brief description of two prototype geocollaborative environments that illustrate the use of the framework developed and provide the basis for discussing goals for further research.

1. Introduction

Recent conceptual and technical developments in information technology have the potential to enable a dramatic change in the role of technology in human-human interaction. (Fischer 2002, Roschelle and Pea 2002, Varian *et al.* 1998). Similarly, developments in geographic information science (GIScience), (Kraak and MacEachren 1999, Mark 1999, MacEachren and Kraak 2000), and in computer graphics/visualization (Brown *et al.* 1999), suggest that we are also on the cusp of a substantial increase in the role of maps, images, and computer graphics as mediators of collaboration, in a range of contexts including scientific inquiry, environmental and urban planning, resource management, and education. In spite of this potential, we have a limited conceptual basis from which to develop or study the use of visually-enabled collaboration (using geospatial or other information).

The primary objectives of this paper are: to outline a conceptual framework for visually-enabled collaboration *with* geospatial information *through* geospatial technologies (an activity that we label *geocollaboration*) and to demonstrate application of this framework to a pair of case studies from our ongoing research. The goal of the framework developed is to delineate important technological,

social, and cognitive parameters that must be considered as we extend, or reinvent, geoinformation technologies to support work by groups. The framework is also intended to provide a structure for understanding the interrelationships among the parameters that define geocollaborative environments, for organizing a systematic program of research in geocollaboration, and for developing approaches to multi-user systems that support rather than impede group work. Particular attention in the framework is given to visual representation as a mediator of group work and we outline an approach to such shared representations grounded in semiotics and theories of boundary objects. We illustrate use of the framework through case studies with two visually-enabled geocollaboration prototypes developed in prior work. One focuses on collaborative visualization and the other on group work using geo-virtual environments (GeoVE).

2. Background

Like Roschelle and Teasley (1995) and Jankowski and Nyerges (2001a), we consider collaborative systems to be a subset of the systems used for computer-supported cooperative work (CSCW). Cooperation can involve any sharing of information, perhaps by individuals performing very different tasks (e.g., an individual using information visualization to find structure in patterns of web activity cooperating with another developing a marketing plan for web advertising). ‘Collaboration’ is used here to identify those cooperative activities in which two or more individuals work together on a single task or closely related subtasks, constructing and maintaining a shared problem conception. Thus, we consider computer-supported *geocollaboration* to involve a committed effort on the part of two or more people to use geospatial information technologies to collectively frame and address a task involving geospatial information.

Our approach to geocollaboration draws upon a diverse literature dealing with group (multi-participant) work. That literature considers collaboration from the perspectives of human sciences, computing, and their integration (Kraemer and King 1988, Mandviwalla and Oldman 1994, Horrocks *et al.* 1999). Like Descortis *et al.* (2000) we contend that a combination of conceptual perspectives, drawn from multiple domains, will be essential for understanding collaborative activity in a specific context or crafting an appropriate collaborative system design methodology for that context. While space does not permit a detailed discussion of the relevant literatures, we direct the reader to theoretical frameworks developed in the domains of distributed cognition (Hutchins 1995), activity theory (Nardi 1996), cognitive ergonomics (Descortis *et al.* 2000) and social aspects of groupware for CSCW (Dix *et al.* 1998). These perspectives, particularly if integrated, have the potential to help isolate and augment specific design issues in collaborative systems.

Within GIScience, there is a growing volume of literature on group work with geospatial information (Nyerges 1999, MacEachren 2000, 2001, Jankowski and Nyerges 2001a). Much of the attention has focused on group spatial decision support (GSDS) (an outgrowth of earlier work in spatial decision support systems (SDSS)), with the focus on design of environments that merge GISystems with multicriteria evaluation methods and decision support tools (Armstrong 1993, Nyerges *et al.* 1997, Jankowski & Nyerges 2001b). While substantial progress has been made in SDSS and GDSS (Jankowski and Nyerges 2001a), limited attention has been given to collaboration focusing on, or mediated by, visual/graphic

displays. Thus the research, generally, fails to address many issues that are likely to be critical for collaboration using the standard tools of GIScience (GISystems, image analysis software, and dynamic maps).

Armstrong and Densham (1995) provide one exception to the lack of attention to visual display for group work with geospatial information, detailing a prototype visual aide to geocollaboration in the context of facility location. However, there seems to have been no direct follow up to their ideas. Some work has also been carried out on development of visual tools to support multicriteria decision-making (Andrienko and Andrienko 2001). The general lack of attention to the role of visual display as a mediator for collaborative work with geospatial information is particularly surprising, since all GISystems use visual, map-based interfaces.

The conceptual framework we detail in this paper will support integration of visual displays as a mediator of group work in a range of domains for which group work with geospatial information is critical. These include science (e.g. environmental change, health-environment interactions, population dynamics), science education, situation assessment and planning for crisis response, as well as decision support for planning and environmental management (traditional application domains for SDSS and GDSS), crisis management and related strategic planning activities. Recent research in two non-GIScience domains provides a base from which to address the potential and challenges associated with visual mediation tools to support geocollaboration in these and other contexts: collaborative visualization and collaboration in virtual environments. Each is discussed below, briefly, with an emphasis on the potential application to visually-mediated geocollaboration.

2.1. Collaborative visualization

Large, distributed multidisciplinary teams now play an important role in scientific work. In the US, for example, there have been calls for geography to direct more attention to ‘big science’ and multidisciplinary collaborations (Wilbanks *et al.* 1997) and a large proportion of science funding is allocated to multi-investigator (collaborative) research projects (e.g. through initiatives dealing with human implications of global environmental change, biocomplexity, digital government, and information technology research). Visualization systems with the potential to facilitate this science have, however, been developed for use by single users.

To meet the needs of interdisciplinary, multi-investigator science as well as planning and decision making, the focus of visualization research and development has begun moving towards support for groups, including distributed groups (Brown *et al.* 1996, Brodlie *et al.* 1998, Rhyne 1998, May 1999, Friesen and Tarman 2000, Watson, 2001, Brodlie forthcoming). However, despite technological successes in the implementation of shared visualization tools (including ones for geospatial data visualization in the contexts of environmental management (Bajaj and Cutchin 1999), oceanographic and meteorological studies (Pang and Fernandez 1995), and hazards research (Padula and Rinaldi 1999)), we know very little about the impacts of shared visualization on group work or how to design effective group geovisualization tools.

Wood *et al.* (1997) propose that the ideal collaborative visualization systems should support both ‘instructor-driven’ collaborations (in which one individual leads a group—termed ‘chauffer-driven’ in the CSCW literature) and interaction among multiple independent participants. For the latter, they suggest that the

environment should support data exchange, shared control, dynamic interaction, ease of learning, and shared application modes. Perhaps the best-tested collaborative system mediated by visualization is the UARC/SPARC collaboratory project (Olson *et al.* 1998). The collaboratory (a virtual laboratory accessible from remote locations, for discussion of development of the collaboratory concept (Cerf *et al.* 1993)) allows users to organize their data streams into hundreds of individualized displays—3D visual renderings and virtual reality rooms—that are then shared (asynchronously) with other collaborators (Olson and Olson 2000). While the UARC/SPARC collaboratory includes collaborative visualization tools, it is designed to support research in physics (thus is not focused on geospatial information) and empirical assessment of the collaboratory tools has not yet focused on the social or cognitive impacts of the role that visualization tools serve in the collaborative process.

In our own previous work (MacEachren *et al.* 1999, Brewer *et al.* 2000), we have focused specifically on development (and usability) of collaborative geovisualization tools to support group data exploration (one of several tasks that might be undertaken in a geocollaborative activity). Some of this work is discussed below as a case study application of the conceptual framework for visually-mediated geocollaboration that we present in §3.

2.2. Collaboration in Virtual Environments

Proponents of Collaborative Virtual Environments (CVEs) contend that such environments have the potential to improve both local and distributed collaborative work significantly (Pantelidis 2000). There are several different display-interaction forms that can be lumped into the category of collaborative virtual environments; these include large screen wall displays, table-top 3D manipulable displays, CAVEs, and Immersadesks. CVEs have been developed for a wide range of applications, examples include: creation of collaborative gaming environments (Szalavári *et al.* 1998); visualization of seismic geoscientific data by co-located individuals (Lin *et al.* 1998); streamed geospatial imagery (Taylor 2001); development of collaborative tools for battlefield analysis (Jones *et al.* 1998); and simulations to facilitate learning about complex environments (Roussos *et al.* 1999). Almost all CVEs rely upon visual displays as a mediator among participants and create ‘spaces’ within which participants interact. Thus they all rely upon spatial metaphors whether or not they depict geospatial data.

Armstrong (2001) argues that teleimmersive distributed environments for working with geospatial information represent a grand challenge that, if met, can enable productive work in many contexts. More broadly, Hindmarsh *et al.* (2000) suggest that high quality graphical display of real and imagined scenes could become the typical every day work medium for distributed interaction among experts. However, these authors also point out that one of the identified barriers to successful CVE implementation is our limited understanding of how people interact with objects, and with each other, in virtual displays.

Research has been undertaken to improve understanding of traditional interaction with geospatial information so that the interaction can be duplicated within a multimodal CVE. For example, Cohen and colleagues (1999, McGee *et al.* 2000) have studied collaborative interaction by Marine Corps commanders with paper maps for command and control operations. The specific goal was to improve the

understanding of interaction with 2D static maps, so that this understanding could guide development and design of a voice, pen, and touch-based interface to a large screen display (McGee and Cohen 2001, McGee *et al.* 2001). Related work on CVEs for collaborative command and control applications (at the US Air Force Research Laboratory) has resulted in a field deployable multimodal system that allows the display and manipulation of real time multimedia data on large screen displays (Jedrysik *et al.* 2000). The goal underlying this work is to link command centre wall displays with field deployable data walls to improve collaboration among multiple commanding agencies.

In an effort focused specifically on support for multiple, interacting users, May (1999) developed the Human Information Workspace (HI-SPACE). HI-SPACE is a large-screen, rear projection, table display environment that supports hands-free, multi-user, untethered interaction with an electronic information space. Two unique aspects of HI-SPACE are its support for multiple, simultaneous cursors and its ability to support integration of physical objects, known as phicons, as part of the rendered scene (figure 1).

In contrast to research on collaborative visualization (which has emphasized software design and implementation), work on CVEs has been more human-centred, directing considerable attention to how CVEs are used and how human behaviour is modified. Associated human-centred research questions that have been addressed deal with: interface design and system usability, support for multi-user

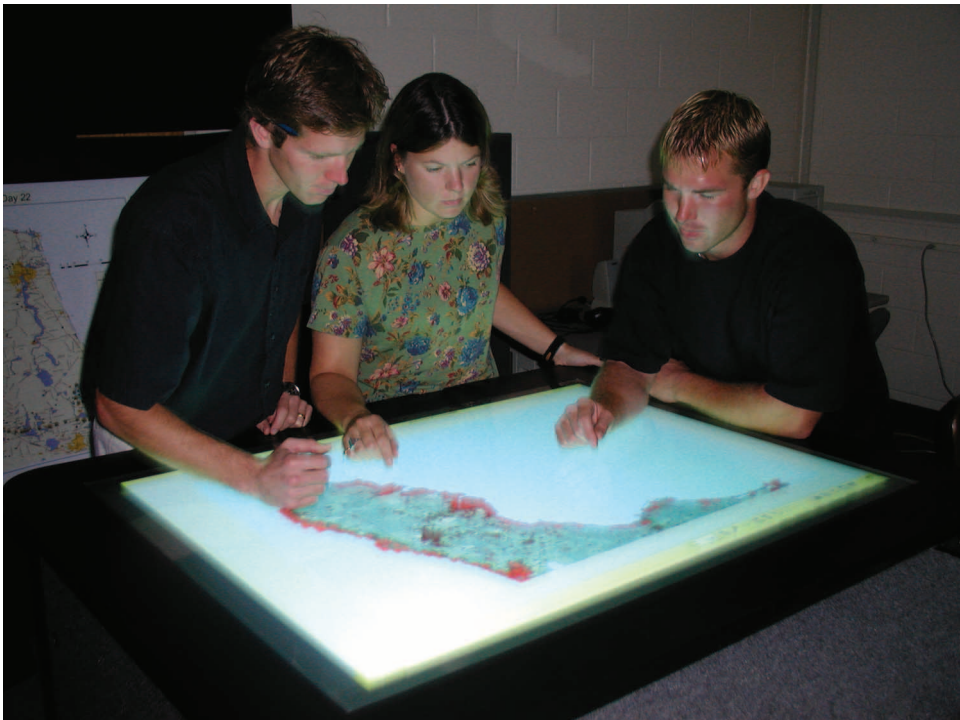


Figure 1. Vision of HI-SPACE group interaction environment. The table display shown is on loan to the Penn State GeoVISTA Center from the Pacific Northwest National Laboratory, and is being used to facilitate joint research on collaborative visualization.

representation and presence, and representation of user's individual views (Park *et al.* 2000)—all topics that are relevant to visually mediated geocollaboration using large screen displays. Related usability and interface design research with CVEs has been directed to the development of 3D human-centred interfaces (Goddard and Sunderam 1999), the use of software agents for enhanced usability (Noll *et al.* 1999), and the design and implementation of metaphors that reduce the cognitive load for participants (Roussos *et al.* 1999). Findings indicate that users within a CVE do not want to be tethered to glove-based or controller-based interaction (e.g. a wand or pointing device). Therefore, a research goal is to develop methods that make interaction with (and within) CVEs more natural.

One of the real barriers to co-located multi-person collaborative work within current CVEs is that the systems often restrict control of the display to one user at a time. Similarly, different-place collaboration within current CVEs is impeded because the nature of social interaction within a CVE differs from that of real (face-to-face) interaction, but current systems do not provide tools to address that difference (Tromp *et al.* 1998). For example, when collaborators are in the same location, they often use gestures to facilitate discussion about objects in the environment, however, when collaborators are in different locations, they must develop alternatives (e.g. verbal expressions or virtual 'gestures') which are often less successful and can interfere with understanding each other's perspectives (Dix *et al.* 1998).

3. Conceptual framework

In this section, we develop a conceptual framework to support visually-enabled geocollaboration. The objective of the framework is to provide a basis from which to design, implement, and understand the use of collaborative geospatial information technologies, with particular attention to dynamic visual displays as mediators for group work.

The collaborative process has many dimensions. Here we identify six that we consider particularly important from the perspectives of both system design and evaluation. The overall approach we take is a human-centred one that puts as much emphasis on the needs of human users as on the technology necessary to meet those needs (Flanagan *et al.* 1997, Brown *et al.* 1999). The first three dimensions of our framework focus on the human components of a collaborative environment and include: problem context, collaboration tasks, and perspective commonality. The second three dimensions (while still attending to users) emphasize the computing infrastructure (e.g. networking, visualization) that can support collaboration, thus they are considered system dimensions. These system dimensions include: spatial and temporal context, interaction characteristics, and tools to mediate group work.

We do not contend that these dimensions represent an exhaustive list. We do believe, however, that they are among the most important for developing geocollaboration environments, testing their usability, and understanding their use and usefulness.

3.1. Problem context

Geocollaboration, as defined above, is an activity that can and should be supported in a variety of problem contexts. Here, we identify four problem contexts within which geocollaboration may be undertaken and for which the nature of that collaboration (and the necessary enabling tools) is likely to differ:

- *knowledge construction and refinement*. The focus here is on tools that facilitate collaborative extraction of information from data and meaning from that information.
- *design*. The focus here is on support for group work directed at creating an entity. Examples include designing a new regional park, designing a new map of US soil productivity, or collaboratively designing a GISystem application.
- *decision-support*. Focus here is on group decisions that make use of geospatial information and its meaning to make decisions about places (e.g. decisions about facility location, distribution of personnel and supplies in a crisis, delineating the bounds of an ecological preserve). Decisions, of course, are also part of both knowledge construction and design.
- *training and education*. The emphasis here is on facilitating group training and learning activities. Examples range from support for earth science education to training for emergency management or military activities.

3.2. Collaboration tasks

A variety of attempts have been made to develop typologies of tasks for group work, see, for example (McGrath 1984, Horrocks *et al.* 1999). While they provide a useful place to start, these typologies address the problem primarily from the context of business management, thus require modification and extensions to fit problem contexts such as scientific knowledge construction, spatial decision support, highway design, or training and education.

For geocollaboration, we have developed a typology of tasks built upon a framework that relates a pair of complementary meta-task categorizations (figure 2). The first, applicable to the contexts of group decision-making and design, borrows from McGrath (1984) who, building on Hackman (1976), delineates four general components within the process of group work, to: generate (ideas and options), negotiate, choose, and execute. The second borrows from MacEachren and Kraak (1997) who, building on earlier work by DiBiase (1990), and Tukey (1977), characterize the uses of geovisualization in support of scientific research as having four stages: exploration, analysis, synthesis, and presentation. These stages complement those identified by McGrath and can be considered stages of group work in knowledge construction and refinement generally. They also are applicable to the development of tools for active, collaborative learning (Fortner and Mayer 1996).

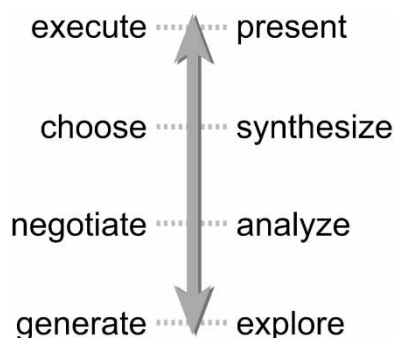


Figure 2. Decision-making tasks matched with knowledge construction tasks.

3.3. Commonality of perspective

The study of human-computer interaction (HCI) often considers participant characteristics that might influence tool and system success. These include physical abilities, user disabilities, cognitive and perceptual abilities, personality differences, cultural and international diversity, and age (Shneiderman 1998) as well as user experience (Nielsen 1993). For collaborative systems, we must consider group characteristics as well as those for individuals. For groups, perhaps the most important distinction to make involves the commonality of perspective held by group members about the problem, the choice of appropriate methods, and the desired outcomes. As McGrath (1984) discusses, group work grounded in cooperation (participants have a shared perspective) is quite different from that grounded in conflict (thus emphasizing negotiation among participants with competing perspectives). Here, we re-characterize this dichotomy as a continuum from conflict to cooperation. (figure 3).

Spatial decisions (e.g. in land use planning, environmental management, highway routing) are generally contentious. Geocollaboration methods and tools for these applications must support not only shared understanding but also resolution of disputes among competing points of view. Scientific knowledge construction by research teams working together toward a common goal is likely to be more cooperative. For such research teams, methods and tools must support innovative thinking as well as comparison and synthesis of what might initially seem to be divergent ideas. As team size grows or becomes more interdisciplinary, the likelihood for tension among competing scientific paradigms will increase, increasing the need for tools that support conflict resolution. Similarly, panels of scientists developing scientific policy may be quite contentious, requiring tools similar to those applicable to any contentious decision-making.

3.4. Spatial and temporal context

The spatial and temporal context of group work activities fundamentally determines the nature, and potentially the success or failure, of geocollaborative work. As pointed out by Ellis *et al.* (1991) (and for geospatial information by Armstrong (1993) and Shiffer (1998)), collaboration can involve participants sharing work at the same or different place and the same or different time (figure 4). For geocollaboration generally, a dynamic visual display becomes the mediator that supports collaboration in these four ‘meeting situations,’ particularly for those that are different-place.

Much of the research directed to geocollaboration has focused on same-time–same-place group spatial decision support, collaborative planning, and similar applications (Armstrong 1993). Nyerges and colleagues (Nyerges 1999, Jankowski and Nyerges 2001a) have pursued a systematic program of research focused on GIS-supported, same-time–same-place collaborative decision making, design and implementation of group systems, and development and application of methods for



Figure 3. The range of perspective commonality that characterizes group work.

	Same Time	Different Time
Same Place	regional planning meeting	military strategic command center
Different Place	multiuniversity team data exploration	asynchronous environmental education project

Figure 4. Sample geocollaboration applications for each of the four space-time situations.

evaluating these systems. Recent advances in geospatial information technology that support large distributed databases and on-line GIS have lead to several prototypes that facilitate different-place collaboration (Jones *et al.* 1997, Churcher and Churcher 1999). Such efforts in GIScience toward different-place collaboration are quite limited and have emphasized using web-based groupware integrated with webGIS (through use of tools such as electronic whiteboards for sketching on maps (Churcher and Churcher 1999, Rinner 2001)).

3.5. Interaction characteristics

Interaction among participants within a geocollaborative environment involves (at least) three interrelated factors. First, is *group size and aggregation* (how many participants are collaborating and what if any subgroups are they organized into?). Second, is the *topology of connections* among group members or subgroups (who is connected to whom?). Connection types include situations with every participant connected to every other (e.g. a group of students using multi-participant chat and electronic whiteboard tools to conduct a class project on regional landuse change), hierarchical networks (e.g. a military command hierarchy where communication between units goes through the unit leader), and many others. Third, are *constraints on form and flow of information* among participants (what promotes or impedes information dissemination crucial to collaboration?) (figure 5). While partly a technological issue, these constraints are often the result of group social structures. For example, different modes of social and cultural organization will impose rules or guidelines that control or constrain information exchange. A democratic collaboration is likely to dictate two-way communication along all links without directional preferences. On the other hand, military hierarchies and other command-and-control applications will give preference to unidirectional communication. For example, communications from a crisis management command centre may contain both information and directives but flows back to the command centre from the field may be restricted only to information.

Social Network Analysis (Wasserman and Faust 1994) provides a formalized approach to support the study and characterization of the relationships, interdependencies, and structure and linkages of individual nodes in a network. Social networks use explanations of the concepts, definitions and processes of how individual social units are linked to one another to identify patterns among relationships, and gain an understanding of the underlying network structure

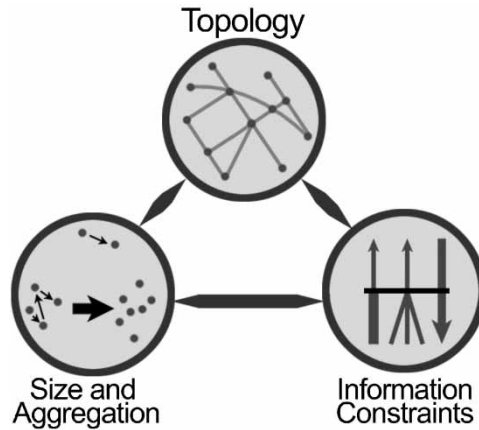


Figure 5. Three key factors in group interaction: topology of participant connections (who is connected to whom), group size and aggregations (how many groups of participants are involved and how big are the groups), and information constraints (what are the technological and social impediments to information flow among participants who share a connection).

(Wasserman and Faust 1994). Another important aspect of the connections among participants is the degree of anonymity allowed or imposed. For related ideas in the context of groupware and multi-user interface design see (Mandviwalla and Oldman 1994, Prates *et al.* 1997).

Within same-time (synchronous) collaboration (whether same- or different-place) the form and flow of information can be further categorized temporally. Possible categories are: (1) sequential interaction, one participant at a time talking and/or manipulating system parameters, (2) simultaneous interaction, multiple participants talking and/or manipulating system parameters at the same time, (3) mixed participation, where one individual controls the display but all can communicate verbally. These categories are conceptually similar to ones proposed by Oviatt *et al.* (1997), for integrating modes of interaction (e.g. speech and gesture) with single-user multimodal systems.

3.6. Tools to mediate group work

Considerable attention has been given to development of tools that mediate and facilitate group work; the literature of CSCW is replete with examples, see: (Grudin 1990, Mandviwalla and Oldman 1994) for overviews. CSCW technologies, often called groupware, can be characterized as information technology that allows people to work together more effectively, with an emphasis on sharing tasks and decision-making (Ackerman 1994). Many of these technologies are generic ones, such as those for Internet chat and video conferencing. Others are targeted to the four problem contexts delineated above: knowledge construction, design, decision-making, and training/learning. We address each below, briefly.

3.6.1. Knowledge construction

Research on groupware to enable knowledge construction has focused on methods and tools that support information sharing, group problem conceptualization, and joint knowledge development strategies, e.g. development of

diagrammatic reasoning methods for structuring work (Shum *et al.* 1997). The OASIS system is among the few efforts thus far to develop groupware for geospatial knowledge construction (Mesrobian 1996). OASIS provides a flexible, extensible object oriented environment for visualization-enabled cooperative work. The project, however, focuses primarily on tools that mediate among heterogeneous software applications rather than on tools that mediate among human collaborators. Our own collaborative visualization efforts also address visual mediation of knowledge construction (and are discussed in more detail in §5 below) (Brewer *et al.* 2000).

3.6.2. Design

Most design work today (e.g. in software engineering or urban development) requires the contributions of multiple individuals with interdisciplinary expertise. Research, however, has just begun to address the role of technology in supporting design teams. Patel *et al.* (1997), in one example, focused on collaborative software design, analysing the functional and nonfunctional requirements necessary for virtual teams to undertake different-place design activities. Their findings indicate that tools—created to help groups develop and understand both task structure as well as the role of collaborators in meeting overall group objectives—assist the process of asynchronous collaborative design and rapid system development.

In work focusing on same-place, synchronous design, Arias *et al.* (2000) have developed a virtual workbench to display map-based information that supports collaborative participatory design of neighbourhood transportation systems and bus stop location. Their research focuses on facilitating shared understanding among co-located design teams by analysing the social and technical aspects of design teams at work on real world geographical problems. They focus particularly on the role of boundary objects (see §4.1 for discussion of boundary objects) and physical externalizations that promote team discussion and collaborative thought development.

3.6.3. Decision-making

Multiple (often conflicting) criteria, diverse participants, and vague problem specifications characterize decision-making situations that involve geospatial information (Xiang *et al.* 1992). A common approach to dealing with these factors is to integrate multicriteria evaluation (MCE) methods and electronic voting tools with GISystems (Jankowski *et al.* 1997). The basic aim of MCE is to integrate multiple, often conflicting, objectives comprising multiple criteria, to indicate decision makers' preferences, and to allow testing of ranked and weighted alternatives (Carver 1991, Jankowski and Richard 1994). While MCE was integrated with GIS in the 1990s (Carver 1991) (note: much of the follow up work in this vein appears under the label SDSS), limited attention has been directed to the role of visual displays as a mediator for the GIS-enabled MCE process specifically or in SDSS or GDSS research, more generally. There is also a clear need for methods that account for mixed information (qualitative and quantitative) in decision-making (Munda 1994). Visual display may be particularly useful as a mechanism through which qualitative information can be integrated into the process.

3.6.4. *Training/Learning*

Work in computer supported collaborative learning (CSCL) has been implemented to support multiple educational levels. In the earth sciences, specifically, Fortner and Mayer (1996) focused on K-12 collaborative learning activities that make use of satellite images to support study of global environmental change. These authors characterized collaborative learning as processes that are *engaging* and that *promote exploration, concept development, elaboration, direct application* and *assessment* (Fortner and Mayer 1996). Collaborative learning tools and online discussion forums to promote distance education are being developed and deployed to educate non-traditional professional students who cannot spend substantial amounts of time away from work (DiBiase 2000, Janicki and Liegle 2001). The supporting tools focus on asynchronous activities and (thus far) typically rely on e-mail for instructor-student collaboration and threaded discussions for student-student collaboration.

4. **Visual mediation for geocollaboration**

As noted above, the role of visualization (or visual representations more generally) as a mediator of group work has been given very little attention. Below, we distinguish between visual, mediating representations that depict the objects of collaboration (information and perspectives on that information) and those representations that depict the activity of collaboration (collaborators and their actions). In §4.1, we consider the use of visual representations as devices through which perspectives can be shared and information meaning rationalized. Next, in §4.2, we consider problems of representing participants and their actions in ways that enable group work (e.g. that facilitate dialogue among participants) while not interfering with the information representations around which collaboration is taking place.

4.1. *Representing information*

Visual representations of geospatial information have the potential to provide a display ‘space’ (frame of reference) within which participants can share and integrate information, compare perspectives, and negotiate approaches and solutions to problems. More specifically, visual displays can be used as:

- *shared objects to talk about*: to depict selected information, provide geo-context, and enable information integration;
- *shared objects to think with*: to develop, clarify, and support structuring of arguments;
- *shared objects to coordinate perspectives and actions*: to compare perspectives, mediate among knowledge domains of participants, link perspectives across scales, and enable joint activity.

This categorization extends one first proposed by Arias and colleague between objects to talk about and think with (Arias *et al.* 2000). Elsewhere, MacEachren (submitted) focused on geovisualization more specifically as the object of collaboration, a device to support dialogue, and a device to support coordinated work.

Armstrong and Densham (1995) present some initial ideas about the role of cartographic representations as mediators for geocollaboration, in the context of group decision-making specifically. They propose a set of new map types designed to facilitate the process of making comparisons among alternative facility location

scenarios, thus map types that act as shared objects to coordinate perspectives (and perhaps subsequent actions).

In what may be the only study thus far to investigate empirically the use of maps and related graphics as mediators for group work with geospatial data, Jankowski and Nyerges (2001b) found that maps were used primarily in the analytic-integration phase of a simulated decision-making process (thus as shared objects to talk about, or perhaps to think with). As the authors point out, the limited role found for maps and graphics in the exploratory-structuring phase of the process may have been due to the particular software configuration used in their study. The configuration grafted their Spatial Group Choice software tools onto a commercial GISystem (ArcView 2.1[®]). It included no extensions (to the ArcView[®] visual display methods and tools), thus, it lacked specific support for group dialogue or for coordinating perspectives or actions. That their results found only limited use of standard GISystem-based mapping tools in a collaborative setting reinforces our point that while groups can adapt to, and use tools built for individual work, such tools will not support group work effectively.

In one of the few attempts to develop visual tools intended specifically to facilitate group work with geospatial information, Rinner (1997, 1999) focuses attention on how to graphically mediate geo-referenced discussions within a planning context (thus on shared objects to think with and, potentially, to coordinate perspectives and actions). He considers geo-referenced discussions to have two primary components: (1) arguments (contained in messages) and (2) geographical objects (e.g. houses, parcels, roads). Rinner's approach to enabling discussion incorporates map-based graphics within a moderated discussion format that uses maps as vehicles for sharing as well as storing information. The prototype system allows users to access map locations to which arguments refer, attach a geographical reference to each new argument, access discussion messages through map symbols that signify geographical objects, and attach new messages to a map object or region.

The dialogues through which groups solve problems or reach consensus with Rinner's environment, or ones like it, are grounded in the *meanings* attached to both geographical objects and arguments in the dialogue. The meanings, in turn, are constructed, shaped, and changed by the interaction of people with each other and with systems that encode the information. To facilitate geocollaboration, attention must be directed to enriching the connections between visual and database representations and between both of these and the meanings (i.e. interpretations) that each user brings to the group situation.

Semiotics, the science of signs (i.e. signification) and sign systems, offers one approach to creating a *semantic framework* through which the meanings associated with geospatial information in collaborative situations can be understood and managed. A fundamental concept in semiotics is the 'semiotic triangle' (Pierce 1955) which itself signifies the three components making up a 'sign,' the *referent*, *sign-vehicle*, and *interpretant* (figure 6). The referent is the entity being represented (e.g. a particular object such as a lake or an abstraction such as a land use category). The sign-vehicle *stands for* the referent; where blue text labels might stand for a specific lake and the colour red might stand for the category 'urban' seen anywhere on the display. The interpretant is the meaning or interpretation derived by a user from the sign-vehicle about the referent. For a comprehensive discussion of the semiotic

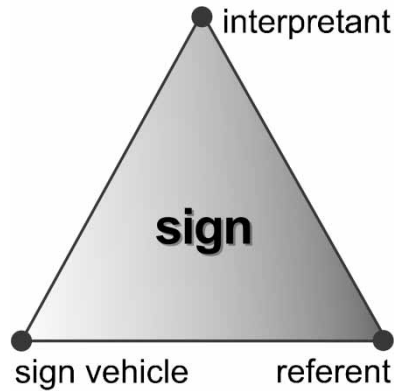


Figure 6. Following Pierce's (1955) triadic approach to signs, a sign can be defined as a relationship among three components, the *semiotic triangle*. First is the *referent*, the object being signified. Second is the *sign vehicle*, the object or device (e.g. a written word, a map symbol) that stands for or signifies the referent. Third is the *interpretant*, the meaning derived from (or perhaps read into) the relationship.

triangle and of semiotics relevant to visual representation of geospatial information, see (MacEachren 1995).

In a collaborative environment, maps and components of maps (e.g. a line depicting a highway on an urban master plan or an isosurface depicting a severe precipitation event in a scientific visualization environment) act as sign-vehicles standing for objects in the world that can serve as the focus of a dialogue. In Rinner's (1997) environment, discussed above, the dynamic link between map objects and arguments provides an explicit connection between the sign-vehicle (the map or map object) and a wider semantic framework within which the interpretant is instantiated. This connection, in turn, increases the potential for map objects (or other visual display elements) to serve as effective external representations of *boundary objects*.

Boundary objects are constructs (partially shared meaning relationships – interpretants in semiotic terms) that provide a meeting ground among perspectives held by different participants in a collaborative activity (Star 1989). They are objects that all parties in a collaborative situation share some understanding of—but often only partially. Thus, they provide an anchor/hook for building greater shared understanding. In the case of Armstrong and Denshem's (1995) cartographic mediators for geocollaboration discussed above, their demand and supply maps are likely to serve as external representations of boundary objects through which participants can structure discussion. All participants have some understanding of the concepts of, and components in, supply and demand and the map depictions anchor those concepts in the characteristics of particular places. By jointly interacting with the map, participants can begin to understand where their conceptions coincide and differ.

Precipitation represents another concept (relevant to our case studies below) that can serve as a boundary object, for example in a dialogue between a climatologist and a hydrologist. The interpretant generated by the sign-vehicle of 'precipitation' (whether spoken, instantiated as text, or instantiated as a coloured region on a map) is similar but not identical for the two individuals. The boundary

object can provide a portal from one perspective to the other (Harvey and Chrisman 1998) and can thus facilitate resolution of conflict. For the example posed above, the common understanding of precipitation provides an initial basis for dialogue while the differences that become apparent as the dialogue progresses help to establish a perspective that might go well beyond this one concept. In this case, the initial display elements instantiate boundary objects to talk about. Perhaps more challenging is the design and implementation of visual tools that instantiate boundary objects to think with and/or to coordinate perspectives, particularly in cases of conflict. A goal for visual tools designed to support coordination of perspective is to provide such boundary objects within an environment that enables identification of differences in interpretants for any sign relationship and (for some applications) reconciliation of those differences (figure 7). One example is use of manipulable visual tools as an interface to parameters of a simulation model, allowing collaborators to iteratively work toward a common understanding of the impact of factors on a process (e.g. the downstream impact of different flood control devices).

For digital geospatial data, the sign relationship is often an indirect one, with the real-world referent signified in the database through some abstract construct and the visual sign vehicle treating that *database sign vehicle* as the referent of a second linked sign. Since current geospatial databases (at least non-experimental ones) provide no mechanism to encode meaning, important information (the interpretant of the database sign relationship) is lost. As a result, the display's human users must rely on a combination of their own prior knowledge, knowledge of their collaborators, and characteristics of the display itself to provide a context for generating an interpretant. Linking map-based sign-vehicles to arguments in a

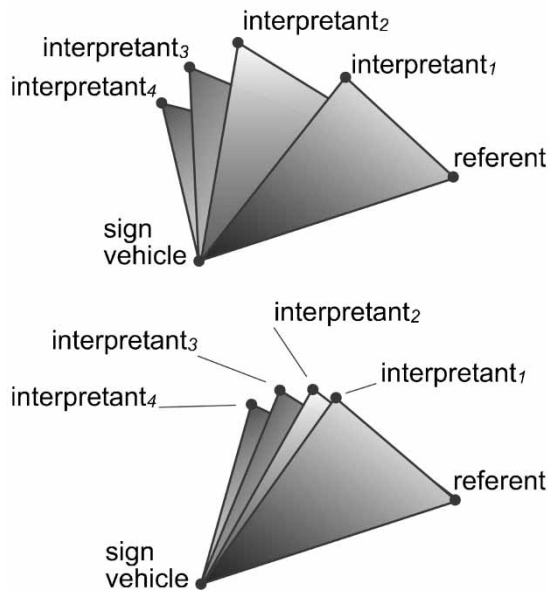


Figure 7. Group semiotic triangles depicting four users with substantially different interpretants for the same sign vehicle-referent relationship (top view) and subsequent convergence of interpretants as a result of joint work.

collaborative setting provides a mechanism through which meaning might be captured and encoded in the database for subsequent use.

4.2. *Representing participants and their actions*

When individuals collaborate in the same-place, without the assistance of technology, they are able to observe each other's actions. This interpersonal contact provides important, often unspoken, information about attitudes, intentions, motivations, and strategies that can facilitate the process of dialogue among the participants. These unspoken cues (shrugs, grimaces, 'ums' and 'uhs') are termed backchannel feedback (Dix *et al.* 1998). Collaborators use such cues to indicate that they are ready to interject, take control, or speak. Dix *et al.* (1998) provide an indepth discussion of the role of back channel feedback in conversations and its incorporation in system design. When technology intervenes, these aspects of normal dialogue are often missing. This absence is obvious for different-place collaboration, where participants might be represented only by an avatar or text ID and their actions represented only by outcomes, with the process of achieving outcomes often hidden. Even in same-place collaboration, technology designed to enhance the experience in some ways can interfere with normal dialogue (e.g. the stereo goggles typically used in an immersive virtual environment restrict the participant's view of anything other than the display screen—for details, see §5.2 below).

Taking full advantage of visual tools designed to facilitate geocollaboration, then, will require attention to the representation of participants and their actions. Such representations must be integrated with displays of the information that collaboration is about, in ways that do not impede participants' abilities to use that information. These representations of participants must provide mechanisms to depict, for each participant:

- their own presence in the environment (providing context against which to judge the location, viewpoint, and perspectives of other participants);
- their own actions on objects in the environment and toward other participants;
- other participant's presence in the environment;
- other participant's deictic actions toward objects, each other, and the user.

Potential representations of participants and actions can take two general forms, representations embedded within the information display (e.g. the avatars and light beam pointers described below for collaborative GeoVirtual Environments) or representations separate from the primary information display. The advantage of the former is that the user's attention can remain on the information display at all times. The disadvantages are that the display is more complex and that some actions cannot be represented effectively within the constraints of the information display. A separate representation of participants and their actions, that can be visible or hidden at the discretion of each participant, is more flexible and can usually encode more information but may distract participants from the primary information display. One example of a minimal representation that limits the potential for distraction from the primary task of group activity is Erickson and Kellogg's (2000) 'social proxy' graph, an abstract depiction of users, their presence,

and their activity; the social proxy graph is visible to all users and represents the relative activity of each in a conversation over time.

For group work with geospatial information, there is a need to represent not only who is participating at what level, but also which representations of data they are using and what they are doing with those representations. We have implemented an initial prototype *participant watcher* designed to support representation and analysis of participants and their actions. The prototype watcher is designed to track the use of a multi-window geovisualization display (specifically a map, scatter plot, and parallel coordinate plot—PCP) used in knowledge construction activities (figure 8).

We are now working on a plan for usability assessment of this and alternative representations of participants and their actions. As with our initial implementation, one anticipated use of the display is for post-session analysis of collaborative work. Our efforts thus far have focused on representing who is interacting, when each participant is interacting, and what each participant is doing. A more challenging task for future research is to represent how the visible user activities relate to user goals within the problem/task context.

5. Case studies

In this section, we present case studies of two visually-enabled geocollaboration prototypes, one building on prior work in collaborative visualization, the other on prior work in GeoVE. The case studies illustrate application of the conceptual framework outlined in §3. In addition, they serve to begin addressing some issues raised in section four concerning how to develop visual mediation methods and tools that support geocollaboration effectively.

Both case studies focus on understanding multi-dimensional space-time environmental data in an effort to achieve new insights concerning environmental processes and to predict (and perhaps mitigate) environmental change. While the prototypes share a focus on group work (by scientists) with spatio-temporal environmental data, they differ in the kinds of technology used (desktop versus semi-immersive large-screen), in the kinds of visual representations used to mediate collaboration (2.5D animation versus 3D integrated space-time views), and in the spatial-temporal context for collaboration (emphasis on different-place-same- and different-time compared to same- and different-place-same-time).

Our goal in this section is not to provide a comprehensive discussion of the research projects highlighted (related discussion appears elsewhere, relevant citations are below). Instead, we use the projects (each of which influenced development of the conceptual framework outlined above) as a vehicle for demonstrating the use and usefulness of the conceptual framework presented and for identifying research questions.

5.1. *Same-time—different-place collaborative geovisualization*

Our first case study focuses on a prototype, desktop, different-place geovisualization environment developed to support collaboration by a team of multidisciplinary scientists as they explore complex spatiotemporal data. The environment consists of a suite of integrated software components designed specifically to facilitate collaboration among users who are exploring time series of climatic data and enable them to share knowledge as they identify patterns and processes (figure 9). The system allows multiple users to control parameters of

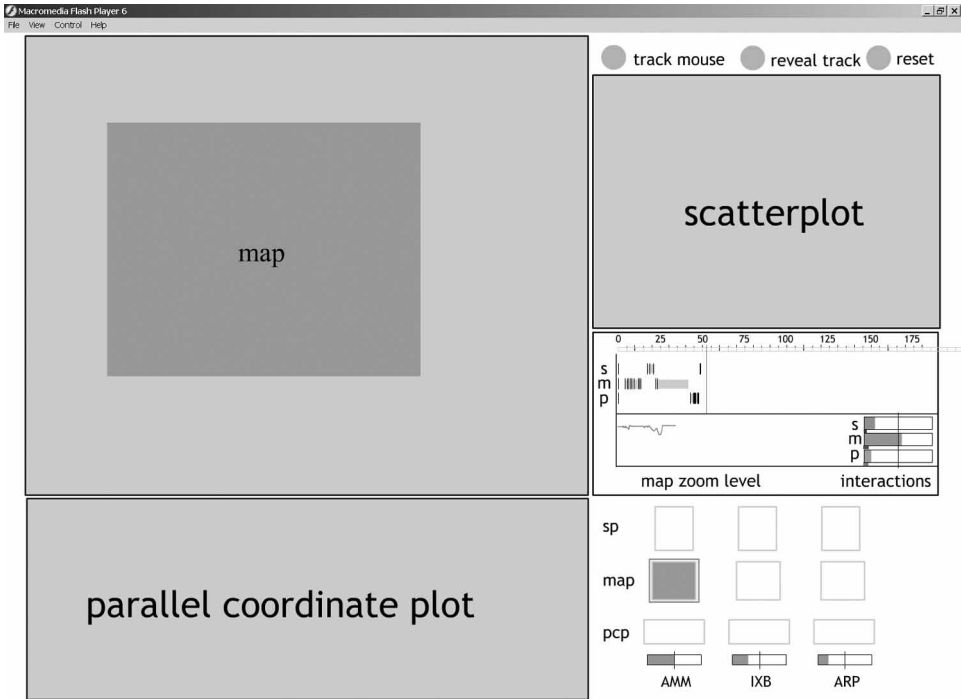


Figure 8. Design prototype collaboration display with activity tracking (controls at top right) and ‘watcher’ tools (2 lower right panels). Created in Macromedia Flash[®]. The prototype includes only placeholders for exploratory data analysis tools. Its purpose is to illustrate the potential of such an observation tool. The two lower right panels provide a dynamic representation of each participant and their collective actions. The bottom panel indicates who is in control and which display component they are interacting with (indicated by the shaded rectangle) as well as the relative proportion of time each participant has been in control. Here, the first participant (AMM) is in control of the display and is interacting with the map. This user has been in control of the display for about half of the session thus far (as indicated by the grey fill in the bars representing each user). The upper watcher panel provides summary information about actions over time. The top half of the panel indicates every mouse click made. For the session depicted, participants focused initial attention on the map (for nearly half of the session to this point). Then attention shifted to the scatter plot (with nearly continuous interaction). Finally, attention moved to the parallel coordinate plot (with a period of consistent interaction followed by alternating periods of inaction and action). The bottom half of the panel illustrates the zoom factor for the map over time, as a user adjusted the scale gradually, then reverted to the default scale. To the right, filled bars represent the proportion of the session during which each display component was the focus of attention. The prototype also tracks mouse movements and allows for replay of those movements. The primary intended application of this watcher tool is to support post session analysis of the collaborative session. This prototype was implemented by Eric Steiner.

temporal database queries and subsequent time series animation, see (Brewer *et al.* 2000, MacEachren *et al.* 2001) for details. Actions (zoom, rotate, classify) performed on one machine are passed to other connected machines through a server-client system. Sections below apply the six-part framework presented above to discussion of this collaborative geovisualization prototype.

5.1.1. *Problem context*

For this case study, two similar applications were targeted: understanding time series temperature and precipitation regimes for the Susquehanna River basin of Pennsylvania, New York and Maryland and understanding monthly temperature patterns for Mediterranean Europe. For both, the scientists with whom we were collaborating were interested in identifying topographical and spatial factors that may affect regional (and global) climate regimes. In relation to the conceptual framework outlined above, this collaborative prototype was designed to support knowledge construction, but extensions have been considered that support risk assessment and decision-making applications as well as science education.

5.1.2. *Collaboration tasks*

During in-depth individual and group interviews with six participating scientists, we elicited responses regarding what types of tasks the scientists would attempt to accomplish when using a distributed map-based data exploration and analysis system. A detailed account of our interview methods and the initial findings is reported in (Brewer *et al.* 2000). Here, we reexamine findings in relation to the four kinds of collaboration tasks detailed above for knowledge construction: explore, analyse, synthesize, and present.

For collaborative *exploration*, one participant discussed the role of maps in the task of brainstorming, or posing ‘what if’ scenarios. Other participants emphasized specific manipulation capabilities needed to support exploration (e.g. dynamically selecting which data to depict, ‘focusing’ on subsets of data) and specific mechanisms that support sharing of ideas (e.g. the ability to highlight features or otherwise draw attention to them).

For collaborative *analysis*, the participants saw map-based computer displays serving as a mediator between different data sources and scales of analysis that would help place all users ‘on the same page’ during collaborative discussions. In addition, split screen views were discussed as a way to support comparison (and coordination) of perspectives. For different-place collaboration, the ability to know what others are doing was seen as important by most participants as was the ability to use voice communication to discuss perspectives.

For collaborative *synthesis* (group work to coordinate perspectives, develop an understanding of differences among perspectives and, where practical, develop a common perspective), substantial differences in typical map/display use across disciplines were noted. Among the more important were the different spatial and temporal scales that disciplines emphasize and the need for collaborative environments to support tools for relating scales. Display format was also an issue discussed. Most users felt that a table-top display would have advantages over a wall display for generating active participation among participants (and active participation should lead to more effective and useful synthesis). Few (if any) existing tools support group synthesis activities, making development of such tools a particular challenge.

For collaborative *presentation*, one participant indicated that we ‘can’t communicate (spatial characteristics) without a map.’ Three participants noted that maps were important for representing temporal (as well as spatial) information (in time series analysis, query by season, or finding cycles and trends). In relation to display format, large screen displays were seen as useful for presentation to groups (with wall displays better than table-top displays for this purpose).

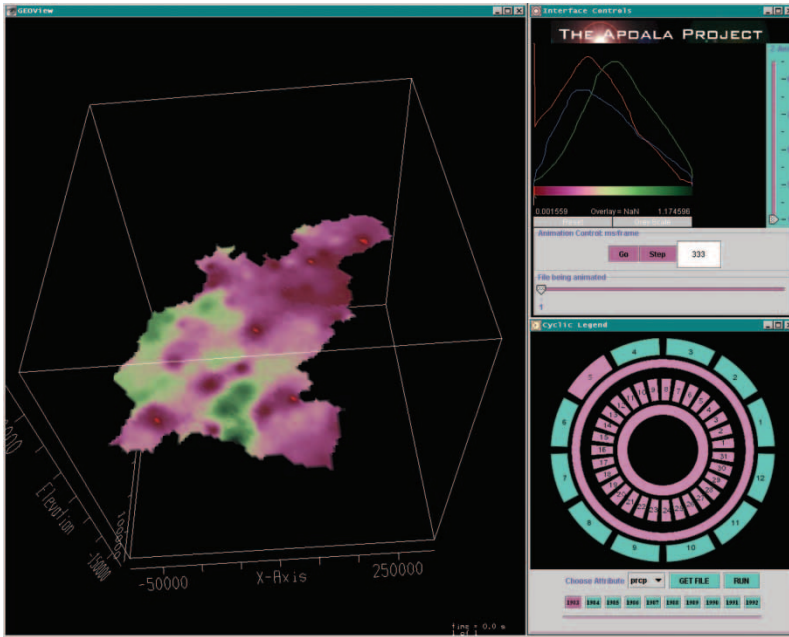


Figure 9. Same time/same place collaboration on linked desktops. Users can manipulate orientation, scaling, and colour schemes of a 2.5D animated depiction that displays, simultaneously, spatially and temporally continuous environmental data (e.g. temperature and precipitation superimposed on an extruded terrain surface). Left panel shows one frame of an animated representation of user-selected climate data (precipitation is shown) draped on a 2.5D terrain depiction. Upper right panel contains controls for color scheme and animation. Lower right panel contains visual query tools that allows user to select subsets of data using a combined linear-cyclic interactive legend (in this case, all days for May, 1993).



Figure 10. Same-place collaboration at a large-screen ImmersaDesk.

Beyond these four tasks, there was consistency across the group in a view that multivariate, multiscale map displays that depict change over time are important prompts for collaborative work in environmental science. Overall, a common idea was that maps help to provide the contextual reference information (boundaries, roads, etc.) to allow interdisciplinary idea sharing. In addition, one participant noted that physical scientists often treat maps as an input to process *modelling* while social scientists consider maps to be *presentational* devices (emphasis added). Thus, disciplinary conventions may have an impact on the mediating role of visual display and the stages of group work where it is most successful.

5.1.3. *Commonality of perspective*

Individual interviews addressed the potential for a distributed collaborative system (derived from the prototype) to support group work on activities that require integrating multiple scientific perspectives. Following from discussion of analysis scales at which different disciplines focus, a key capability for collaboratively exploring environmental processes is to support representation of connections among processes across scales. A second issue raised was the need to support both individual work (allowing individuals to develop their ideas in a private display space before sharing them with the group) and comparison of perspectives (e.g. thus the ability to broadcast that display to the entire group for discussion and possible synthesis).

5.1.4. *Spatial and temporal context*

As noted above, the focus of this case study was on same-time–different-place collaboration. Interview results, however, also indicated that participants could envision using the system for a range of collaborative situations. Situations discussed included same-time–same-place planning and decision-making (particularly as enabled by large screen displays) and different-time (both same- and different-place) joint work on meeting preparation (particularly in support of environmental planning). Since planning processes often involve multiple meetings and discussions, the system could be used to build and retrieve a record of activities leading to a decision (given tools to create annotated histories).

5.1.5. *Interaction characteristics*

The prototype system provides a variety of topological connection possibilities. The client server system can support a relatively large number of connections (>10). With the current implementation, there is no built-in method for establishing user control. Thus, the first user to initiate an action controls all functions, until they release the mouse. Collaboration among three or more users would probably be somewhat chaotic unless an ‘etiquette’ for shared control could be achieved (we have only tested the system with pairs of users). The system does have a function that allows one operator (a moderator) to control every other operator’s access privileges. The moderator can make participants active or inactive. During our interviews, participants indicated that it was essential for users of a distributed system to know who has control and that there be a formal method for gaining and relinquishing system control, so that single individuals cannot dominate the collaboration.

We suggest that, until mechanisms and affordances are developed to support

practical shared control of a distributed collaborative system, co-equal interaction will be most practical for groups of three or less. The number of participants could increase substantially, however, for instructor-led collaboration. For example, if the system described here were used for same-time–same-place collaboration in which every participant had his or her own display, an instructor, team leader, or moderator could use the ‘make active / inactive’ function to allow one participant at a time to manipulate the system for shared questions and discussion. Another possibility is to let the natural flow of conversation dictate who has control by maximizing back channel feedback in small group settings. The integration of more natural conversational practices and norms into the interface design could potentially improve collaborative work.

5.1.6. *Tools to mediate understanding*

The results of our interviews made it clear that several necessary tools for mediating understanding were missing from the prototype. In addition to the need for an indication of who was in control and a mechanism for sharing control (both mentioned above and implemented in the prototype participant watcher discussed in §4.2), participants also requested a suite of drawing and selection tools. To facilitate effective member-to-member communication, participants also asked for integration of video conferencing, telephone, and online chats and message boards. Tools for attracting group attention were also suggested to be extremely important. Moreover, participants asked for domain specific representations (and a way to compare them), so that collaborators with different backgrounds could bring themselves, or the group, up to speed on concepts and terminology. Particular attention was placed on the ways in which individual users could direct or attract attention of the entire group. The need to represent individual participants and their actions was discussed by most participants. While avatar representations were an option considered, most participants advocated some form of simpler color-coding as the desired mode for representing individual users.

5.2. *Same-time–same- and different-place collaborative GeoVE*

Our second case study focuses on the use of large-screen immersive VE technology (specifically an ImmersaDesk, IDesk for short) to facilitate group discussion about environmental processes. We had the opportunity to test this environment for both same-place and different-place group work focused on exploratory analysis of times series geospatial data. For more details on the conceptual approach to GeoVE developed, see: (MacEachren *et al.* 1999). The different-place collaboration was achieved through assistance of environmental and computer scientists at Old Dominion University (Cathy Lascara, Glen Wheless, and their staff) who developed Cave5D, the software environment used (Wheless *et al.* 1996). Using high speed internet connections, two separate tests were conducted, one linking our IDesk with another IDesk at Old Dominion and a second linking our IDesk with one at the University of Iowa (working with Marc Armstrong, Judy Brown, and their students/staff) (figure 10). As we did for the first case study, we apply the conceptual framework presented above to identify a set of key issues to consider for geocollaboration supported by VE technologies.

5.2.1. *Problem context*

The problem context for this case study was, as above, knowledge construction and refinement. The application domain was regional climate processes, specifically spatiotemporal relationships between temperature and precipitation. Data used included daily temperature and precipitation values (from May through July, 1972), again for the Susquehanna River basin. An issue of particular interest to the scientists with whom we were collaborating was the precipitation-temperature relationships associated with Hurricane Agnes as it impacted the basin and comparison of these relationships to those for smaller scale (ordinary) storms associated with mid-latitude cyclones moving across the region.

The functionality provided by an IDesk using Cave5D as the software development environment imposed substantial limits on the ability of collaborating individuals to work on a simulated knowledge construction task—primarily due to the interaction characteristics of the environment (see below). Our conclusion here is that the IDesk environment, as tested, is better suited to instructor-led situations than to those with multiple independent participants (thus to training and education or command and control applications rather than scientific exploration applications). This conclusion will be elaborated in sections below.

5.2.2. *Collaboration tasks*

The initial methods and tools implemented were ones intended to support same-place dialogue related to knowledge construction, thus dialogue focused on data exploration. The primary exploration goals in our case study were to understand the space-time relationships of each attribute and the interrelationships between attributes over time.

The Cave5D software used supports a rather small range of display and interaction forms. Using the available 3D display capabilities, terrain was mapped to an x - y - z extruded surface (using only a small portion of the z -dimension of the view). Above this terrain depiction, x and y continued to represent latitude and longitude while time was mapped to the remainder of the z dimension (figure 11). In this space-time portion of the display space, the olive green ‘clouds’ are space-time precipitation isosurfaces (regions in space-time with precipitation above a threshold value). Hurricane Agnes is the largest event, spatially covering the entire Susquehanna River basin and lasting for several days (a regional ‘blanket’ of rain multiple days thick). The blue-yellow layer floating above the hurricane event depicts temperature, using a spectral colour scheme in which blue depicts cool, yellow intermediate, and red high temperatures.

The implementation supports three kinds of exploration tasks. First, users can visually inspect the 3D information structure by rotating the display object as if the representation was a physical model being manipulated in the hand. Second, investigation of the relationships among attributes is supported by the ability to drag layers (time slices in this case) through the precipitation display. The third kind of exploration task supported is detailed investigation of spatial and temporal characteristics of space-time events, through changes to the isosurface threshold used.

Our experience with simulated exploratory knowledge construction tasks in this prototype highlighted a fundamental difference between task typologies for decision-making and those to support knowledge construction. For decision-making, decades of attention have been devoted to the process of group work and

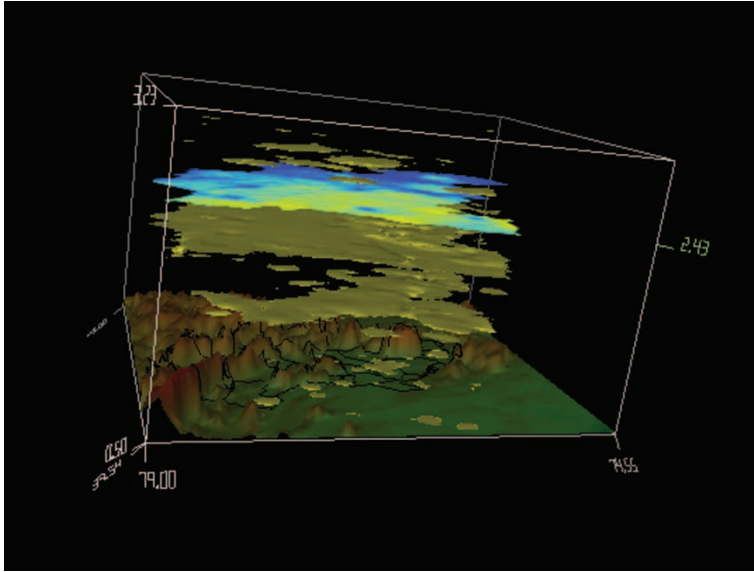


Figure 11. Terrain depiction (lower portion of display) merged with space-time representation of precipitation (green isosurfaces) and temperature (yellow-blue layer), with x - y representing geographical position and z representing three months of time. The threshold value for the isosurfaces can be manipulated by the users; a tighter threshold acts to visually isolate the core precipitation regions (in space and time), thus those most likely to have generated immediate flash flooding (deep in time) and those likely to generate more sustained flooding (broad in space). The temperature layer can be moved through time by clicking and dragging. Dragging the layer up through the hurricane event easily highlights short-term evaporative cooling that follows the hurricane. What surprised our earth science colleagues about the display was that it also allowed them to visually explore the similar, but much more subtle, cooling associated with local thunderstorms (even though the data depicted are at daily temporal resolution).

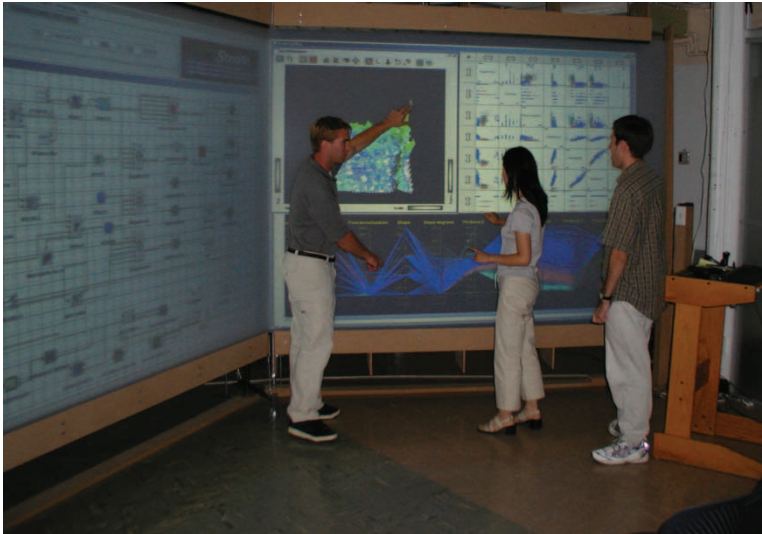


Figure 12. Same-place collaboration at a dual, large-screen stereo display.

we have relatively sophisticated group decision-making task typologies as a result of that effort. With knowledge construction, however, both the tools and the terminology we use to describe the process have focused on the individual scientist. While there has been research to develop typologies of tasks related to visual data exploration (Keller and Keller 1992, Knapp 1995, Qian *et al.* 1997) and to geospatial data use more generally (Albrecht 1995), these typologies have not addressed tasks that are specific to group work, such as choosing among or synthesizing potentially contradictory explanations for an apparent relationship seen in the display. Just as efforts to isolate specific group decision-making tasks from one another have supported development of tools targeted at each group decision-making task, a similar effort to delineate knowledge construction tasks at the level of group interaction is essential. Such a typology, if collectively developed by the GIScience community, would help us move from geospatial technologies that support individual scientists to technologies that support scientific teams.

5.2.3. *Commonality of perspective*

This case study was restricted to situations in which there was a relatively high commonality of perspective among participants, specifically climatologists using a shared scientific paradigm to pursue narrow data exploration tasks. The prototype emphasized support for direct interaction with the visual display. Due to the expected high commonality of perspectives little attention was directed to tools that help to share points of view, explain what is being seen, or integrate different perspectives and interpretations. As noted above in discussion of the first case study, however, we are beginning to address the more challenging goal of visual display support for multiple scientific perspectives. Our current work addresses this issue in the context of large-screen, non-immersive GeoVE (see §6 below).

5.2.4. *Spatial and temporal context*

The prototype considered in this case study, was developed initially to support same-place–same-time collaboration. The primary advantage of the IDesk environment for this application (over a standard desktop display environment) proved to be the large screen. Its size (and upright orientation) allowed multiple people to simultaneously share a similar view of the data. A disadvantage for same-place group work is that use of stereo glasses limits participant's ability to carry on a normal dialogue about what they are seeing; because they cannot take advantage of gestures and facial expressions as fully as if participants were discussing a large paper wall map.

As noted, multiple IDesks were linked (using high-speed Internet connections) to support different-place–same-time applications (in our trials, we have used only two at a time, but the technology supports more). Remote collaboration requires tools that support a dialogue. We opted initially for Internet tools that supported real-time voice communications. The latter proved to be unreliable and we often resorted to a pair of speaker telephones to communicate among multiple participants working with each display. While voice-only dialogues might at first seem to add a constraint on collaboration not faced in the same-place situation, the use of stereo glasses (as noted above) constrains same-place dialogue using an IDesk in a similar way.

5.2.5. Interaction characteristics

The IDesk and network technologies put specific constraints on interaction characteristics. For same-place use, only one individual has control of the display at a time (for convenience, referred to as the *guide* below) and the *hand off* of control from one user to another interrupts any dialogue that is taking place. The guide must not only hand the control ‘wand’ to another user but also switch glasses with them, since (at least with our hardware implementation) a physical wire connects the head tracking unit to one pair of glasses. The environment, thus, favors an interaction topology in which one person controls the dialogue (thus an instructor-led situation).

Group size is restricted to perhaps 3–5 individuals by display size and the optimal viewing position (about one metre from the display and keyed to the location of the control glasses worn by the guide). Picture quality deteriorates rather quickly from this location (with the coherence of the stereo view decreasing and the likelihood that users will become nauseous increasing proportionally). Similarly, the sense of immersion decreases with distance from the screen.

For different-place collaboration, each guide can adjust their site’s viewpoint independently (by zooming, panning, and rotating). In addition, each guide can control which information layers are visible locally as well as globally. This capability meets a need identified in previous interviews (case study 1), to provide a mechanism that supports independent work (local viewing) prior to showing that work to all collaborators (global viewing). The implementation is, however, quite limited because participants at any one site see an identical view and it is not possible to toggle between an in-progress view and the shared view, other than by turning each information layer completely on or completely off globally.

Overall, for different-place group interaction, the IDesk/Cave5D environment is best suited to situations in which each group is organized with a team leader who acts as moderator for collaboration from one team to another. With a voice link, of course, any individual on one team can direct a comment or question to any individual on another team, but without control of the display the potential to answer effectively is limited.

5.2.6. Tools to mediate understanding

An IDesk combined with Cave5D software provides only limited tools to visually mediate understanding. The software was developed for use in single-user desktop display, and then ported to multi-walled ‘Caves’ and to the IDesk hardware platform (still with an underlying single user structure). Even with enhancements that support multiple locations, these single user roots remain apparent and limiting. The environment provides only two specific features to support same-place collaboration.

First, the screen size allows 2–5 individuals to be near enough to the screen to use ordinary pointing gestures as a means to draw each other’s attention to features being discussed. Second, the guide can make use of a laser pointer-like device to pinpoint features being discussed. This pointer appears more similar to a light-saber from Star Wars than to a standard laser pointer, because it generates a long narrow light beam in 3D space. This remote pointer supports some of the functionality that Florence, et. al (1996) envisioned for ‘wallboards’ (used at ‘spitting distance’), but with substantial limits. Like a light-saber, its beam has a fixed length. Thus, the

only way to point at a feature in the foreground is for the guide to move their hand away from the screen. It is usually easier to pierce an object of interest than to point at it.

For different-place collaboration, each guide is represented by one light beam. The beam at any location will appear (to those at that location) to enter the field of view from the guide's location, thus the origin of the beam will not be visible to the local participants. For beams representing remote team guides, participants see the beam plus a small avatar. The location of the avatar represents the team guide's viewpoint and the beam represents the guide's direction of view. This rather abstract representation (based on our informal experience) seems to be quite effective in helping each team identify the perspective from which other teams are viewing the scene and (together with voice communication) in helping to arrive at a shared perspective.

6. Discussion and ongoing research

The overall goal of the conceptual framework for visually-enabled geocollaboration presented here is to guide the design, implementation, and assessment of geocollaboration environments. The conceptual framework supports a structured approach to each stage of the design, implementation, and assessment process. Attention is paid to both the human components of the collaborative environment (problem context, collaboration tasks, and perspective commonality) and the system components that can support or impede collaboration (spatial and temporal context, interaction characteristics, and tools to mediate understanding).

The use of the conceptual framework developed was illustrated through application to post-hoc analysis of two prototypes, one focused on different-place—same- and different-time collaborative geovisualization and the other on same-time—same- and different-place collaborative GeoVE, both applied to knowledge construction. This post-hoc analysis provided the basis for discussing strengths and weaknesses of particular methods and tools applied to environmental science. More importantly, however, this exercise helps to identify a set of research and IT/HCI development challenges related to visually-enabled geocollaboration.

Among the most important overarching research challenges are the following:

- To develop a theoretical understanding of the cognitive and social aspects of both local and remote collaboration mediated through display objects in a geospatial context;
- To develop approaches to multi-user system interfaces that support rather than impede group work;
- To understand the ways in which characteristics of methods and tools provided to support collaboration influence the outcome of group work.
- To initiate a parallel, concerted effort focused on integrating, implementing, and investigating the role of the visual, geospatial display in collaborative science, education, design, and group decision support (GDSS);

We believe that meeting these goals will require an interdisciplinary approach that draws upon and contributes to advances in a range of domains including CSCW, CSCL, GDSS, ergonomics, cognitive system engineering, and distributed cognition.

Within the overarching challenges detailed above, we also identify a series of specific visualization, HCI, and information technology objectives:

- If visual displays are to serve effectively as mediators for geocollaboration, it is essential to:
 - Assess the advantages and disadvantages of extending methods of interactive geographical and information visualization (developed for single users) to collaborative settings and compare such extensions with new methods designed specifically to meet the unique characteristics of group work;
 - Examine the role of different kinds of visual representation (realistic versus abstract, animated versus static) and related virtual environment methods and technologies in geocollaborative settings;
- Because available control devices and kinds of interaction supported in current visually-enabled collaborative environments rely on desktop metaphors, they impede dialogue, for example using popup ‘dialog’ boxes for achieving actions such as turning display of layers on and off. More natural interfaces that allow users to direct attention to (and talk about) the information being displayed, rather than to using the system, are needed to facilitate dialogue.
- New interaction devices are needed that support multiple users in the same place at the same time. This is particularly necessary to support multiple co-equal collaborators (rather than instructor-led collaboration).
- For situations with low commonality of perspectives, interfaces must do more than help collaborators realize each others’ viewing location. Tools are needed to help them understand and share differing conceptual perspectives.

We have begun to experiment with three environments that address the challenges identified. All use large screen display but de-emphasize immersion (by omitting the head tracking used with the IDesk display). One of these environments is the HI-SPACE table described above (figure 1). By allowing integration of physical objects (phicons) with the visual display and supporting multiple users at once, the HI-SPACE table decreases some of the impediments to group work found in our early prototype tools. The HI-SPACE environment was designed for same-place collaboration and we are now working with colleagues at PNNL to extend it for different-place collaboration using linked tables.

The second environment we have begun to use is a new large-screen VE constructed by our collaborators in the Center for Academic Computing at Penn State (figure 12). This new environment is not dependent on the Cave library. Instead, we can use any software capable of generating 3D depictions. We are now using our Java-based *GeoVISTA Studio* software to develop stereo applications for group work (Takatsuka and Gahegan 2002). The hardware implementation uses a pair of non-immersive, large-screen, stereo displays (driven by two pairs of rear-projection video projectors). The displays are viewed with polarized glasses. The lack of head tracking (and absence of wires between glasses and display) makes collaboration among users more balanced (i.e. the environment is useful for both instructor-led collaboration and group work among equals). Although one user is still in control (using a gyro mouse), it is much easier to trade off that control and the display is not constantly readjusting its perspective to that of one user while he or she moves

around. The dual display facilitates work by larger groups and, as shown, facilitates discussion of both the visual representation of data (right screen) and the visual program used to process and display those data (left screen). The environment is also an order of magnitude less expensive than an IDesk (roughly \$25 000 U.S. rather than \$250 000+ US).

The objective for the third environment, *Dialogue-Assisted Visual Environment for Geoinformation (DAVE_G)*, is to provide more natural, multi-user interfaces to spatial information. The specific research goal is to develop principles for implementing and assessing natural, multimodal, multi-user dialogue-enabled interfaces to geographical information systems that make use of large-screen displays and virtual environment technology. The *DAVE_G* project incorporates computer vision and speech processing as a means of interpreting and integrating user input from spoken words, free hand gestures and gaze. The practical goal for this research is to support decision-making tasks by experts and the general public. For more details, see: <http://www.geovista.psu.edu/grants/nsf-itr/index.html> and (Rauschert *et al.* 2002).

As discussed above, past research on group work with geospatial information has not focused on the role of maps and other visual display forms. The potential of visual display to enable geocollaboration is, however, beginning to be recognized (MacEachren and Kraak 2001, Muntz *et al.* 2003). As outlined in these reports, a fundamental challenge for GIScience and related information sciences is to: (1) understand the roles for visual display and the types of display environments best suited to geocollaboration (i.e., large screen, table top, wall displays, VR), and (2) to implement and assess visually-enabled geocollaboration environments suited to a range of problem contexts and tasks.

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References

- ACKERMAN, F. editor, 1994, *Working Together through Groupware* (Westport, CT: Praeger).
- ALBRECHT, J., 1995, Universal GIS operations: task-oriented systematization of GIS functionality. Unpublished PhD, University of Vechta, Germany.
- ANDRIENKO, G., and ANDRIENKO, N., 2001, Interactive visual tools to support spatial Multi-criteria Decision Making. In *User Interfaces to Data Intensive Systems*, pp. 127–131.
- ARIAS, E., EDEN, H., FISCHER, G., GORMAN, A., and SCHARFF, E., 2000, Transcending the individual human mind – creating shared understanding through collaborative design. *ACM Transactions on Computer-Human Interaction*, 7, 84–113.
- ARIAS, E. G., and FISCHER, G., 2000, Boundary objects: their role in articulating the task at hand and making information relevant to it. In *Proceedings of International ICSC Symposium on Interactive and Collaborative Computing (ICC'2000)* (University of Wollongong, Australia: ICSS Academic Press), pp. 567–574.

- ARMSTRONG, M. P., 1993, Perspectives on the development of group decision support systems for locational problem-solving. *Geographical Systems*, **1**, 69–81.
- ARMSTRONG, M. P., 2001, The four way intersection of geospatial information and information technology. *White paper prepared for NRC/CSTB Workshop on Intersections between Geospatial Information and Information Technology*, 19 September, 2001. http://www7.nationalacademies.org/cstb/wp_geo_armstrong.pdf
- ARMSTRONG, M. P., and DENSHAM, P. J., 1995, Cartographic support for collaborative spatial decision-making. *Auto Carto 12, ACSM/ASPRS Technical Papers*, **4**, pp. 49–58.
- BAJAJ, C., and CUTCHIN, S., 1999, Web based collaborative visualization of distributed and parallel simulation. *IEEE Parallel Visualization and Graphics Symposium* (Los Alamitos, CA: IEEE), pp. 47–54.
- BREWER, I., MACEACHREN, A. M., ABDO, H., GUNDRUM, J., and OTTO, G., 2000, Collaborative geographic visualization: enabling shared understanding of environmental processes. *IEEE Information Visualization Symposium* (Los Alamitos, CA: IEEE), pp. 137–141.
- BRODLIE, K., in press, Models of collaborative visualization. In *Exploring Geovisualization*, edited by J. Dykes, A. M. MacEachren and M.-J. Kraak (Amsterdam: Elsevier).
- BRODLIE, K. W., DUCE, D. A., GALLOP, J. R., and WOOD, J. D., 1998, Distributed cooperative visualization. *State of the Art Reports at Eurographics*, **98**, pp. 27–50.
- BROWN, C., BENFORD, S., and SNOWDON, D., 1996, Collaborative visualization of large scale hypermedia databases. *Proceedings of the ERCIM workshop on CSCW and the web*. [pp. orgwis.gmd.de/projects/W4G/proceedings/visual.html](http://orgwis.gmd.de/projects/W4G/proceedings/visual.html).
- BROWN, J. R., VAN DAM, A., EARNSHAW, R., ENCARNACÃO, J., GUEDEJ, R., PREECE, J., SCHEIDERMAN, B., and VINCE, J., 1999, Human-centered computing, online communities and virtual environments, special report on the First Joint European Commission/National Science Foundation Advanced Research Workshop, June 1–4, 1999, Chateau de Bonas, France. *Computer Graphics*, **33**, 42–62.
- CARVER, S., 1991, Integrating multi-criteria evaluation with geographical information systems. *International Journal of Geographical Information Systems*, **5**, 321–339.
- CERF, V. G., CAMERON, A. G. W., LEDERBERG, J., RUSSELL, C. T., SCHATZ, B. R., SHAMES, P. M. B., SPROULL, L. S., WELLER, R. A., and WULF, W. A., 1993, *National Collaboratories: Applying Information Technology for Scientific Research* (Washington, D.C.: National Academies Press).
- CHURCHER, C., and CHURCHER, N., 1999, Realtime conferencing in GIS. *Transactions in Geographic Information Systems*, **3**, 23–30.
- COHEN, P., MCGEE, D., OVIATT, S., WU, L., CLOW, J., KING, R., JULIER, S., and ROSENBLUM, L., 1999, Multimodal interaction for 2D and 3D environments. *IEEE Computer Graphics and Applications*, **July/August**, pp. 10–13.
- DESCORTIS, F., NOIRFALISE, S., and SAUDELLI, B., 2000, Activity theory, cognitive ergonomics and distributed cognition: three views of a transport company. *International Journal of Human-Computer Studies*, **53**, 5–33.
- DIBIASE, D., 1990, Visualization in the earth sciences. *Earth and Mineral Sciences, Bulletin of the College of Earth and Mineral Sciences, Penn State University*, **59**, 13–18 (also: www.geovista.psu.edu/publications/others/dibiase90/swoopy.html).
- DIBIASE, D., 2000, Is distance education a Faustian bargain? *Journal of Geography in Higher Education*, **24**, 130–135.
- DIX, A. J., FINLAY, J. E., ABOWD, G. D., and BEALE, R., 1998, *Human-Computer Interaction*, 2nd edition (Englewood Cliffs: Prentice Hall).
- ELLIS, C. A., GIBBS, S. J., and RELN, G. L., 1991, Groupware: Some issues and experiences. *Communications of the ACM*, **34**, 39–58.
- ERICKSON, T., and KELLOGG, W. A., 2000, Social translucence: designing systems that support social processes. *ACM Transactions on Computer-Human Interaction*, **7**, 59–83.
- FISCHER, G., 2002, External and sharable artifacts as sources for social creativity in communities of interest. In *Proceedings of the Fifth International Roundtable Conference: Computational and Cognitive Models of Creative Design*, pp. 9–13. <http://www.cs.colorado.edu/~gerhard/papers/ccmcd2001.pdf>
- FLANAGAN, J., HUANG, T., JONES, P., and KASIF, S., 1997, *National Science Foundation*

- Workshop on Human-Centered Systems: Information, Interactivity, and Intelligence* (2 July 1997). Available: www.ifp.uiuc.edu/lnsfhcs/final_report/toc.html.
- FLORENCE, J., HORNSBY, K., and EGENHOFER, M. J., 1996, The GIS wallboard: interactions with spatial information on large-scale displays. In *International Symposium on Spatial Data Handling*, edited by M. J. Kraak and M. Molenaar (London: Taylor and Francis), 7, 449–463.
- FORTNER, R. W. M., and MAYER, V. J., 1996, Constructing Earth system science learning through multidisciplinary studies of global change. *Geoscience and Remote Sensing Symposium, 1996. IGARSS '96. 'Remote Sensing for a Sustainable Future.'* (Los Alamitos, CA: IEEE), pp. 1166–1168.
- FRIESEN, J. A., and TARMAN, T. D., 2000, Remote high-performance visualization and collaboration. *IEEE Computer Graphics and Applications*, July/August, 45–49.
- GODDARD, T., and SUNDERAM, V. S., 1999, Toolspace: Web based 3D collaboration. In *Proceedings of Fourth International Conference on the Virtual Reality Modeling Language and Web 3D Technologies*. <http://www.c-lab.de/vrml99/home.html>
- GRUDIN, J., 1990, Groupware and cooperative work: problems and prospects. In *The Art of Human-Computer Interface Design*, edited by B. Laurel (Reading, MA: Addison-Wesley), pp. 171–185.
- HACKMAN, J. R., 1976, Group influences on individuals. In *Handbook of Industrial and Organizational Psychology*, edited by M. D. Dunnette (Chicago, IL: Rand-McNally), pp. 1455–1525.
- HARVEY, F., and CHRISMAN, N., 1998, Boundary objects and the social construction of GIS technology. *Environment and Planning A*, 30, 1683–1694.
- HINDMARSH, J., FRASER, M., HEATH, C., BENFORD, S., and GREENHALGH, C., 2000, Object-focused interaction in collaborative virtual environments. *ACM Transactions on Computer-Human Interaction*, 3, 477–509.
- HORROCKS, S., RAHMATI, N., and ROBBINS-JONES, T., 1999, The development and use of a framework for categorising acts of collaborative work. In *Proceedings of the 32nd Hawaii International Conference on System Sciences* (Los Alamitos, CA: IEEE Computer Society).
- HUTCHINS, E., 1995, How a cockpit remembers its speeds. *Cognitive Science*, 19, 265–288.
- JANICKI, T., and LIEGLE, J. O., 2001, Development and evaluation of a framework for creating web-based learning modules: A pedagogical and systems perspective. *Journal of Asynchronous Learning Networks*, 5, 58–84.
- JANKOWSKI, P., and NYERGES, T., 2001a, *Geographic Information Systems for Group Decision Making: Towards a participatory, geographic information science* (New York: Taylor & Francis).
- JANKOWSKI, P., and NYERGES, T., 2001b, GIS-supported collaborative decision-making: results of an experiment. *Annals of the Association of American Geographers*, 91, 48–70.
- JANKOWSKI, P., NYERGES, T. L., SMITH, A., MOORE, T. J., and HORVATH, E., 1997, Spatial group choice: A SDSS tool for collaborative spatial decision-making. *International Journal of Geographical Information Science*, 11, 577–602.
- JANKOWSKI, P., and RICHARD, 1994, Integration of GIS-based suitability analysis and multicriteria evaluation in a spatial decision support system for route selection. *Environment and Planning B*, 21, 323–340.
- JEDRYSIK, P. A., MOORE, J. A., STEDMAN, T. A., and SWEED, R. H., 2000, Interactive displays for command and control. *Aerospace Conference Proceedings* (Los Alamitos, CA: IEEE), pp. 341–351.
- JONES, P. M., HAYES, C., WILKINS, D., BARGAR, R., SNIJEK, J., ASARO, P., MENGSHOEL, O., KESSLER, D., LUCENTI, M., CHOI, I., TU, N., and SCHLABACH, M., 1998, CoRAVEN: Modelling and design of a multimedia intelligent infrastructure for collaborative intelligence analysis. In *Proceedings of the 1998 IEEE International Conference on Systems, Man, and Cybernetics* (Los Alamitos, CA: IEEE), pp. 914–919.
- JONES, R. M., COPAS, C. V., and EDMONDS, E. A., 1997, GIS support for distributed group-work in regional planning. *International Journal of Geographical Information Science*, 11, 53–71.
- KELLER, P., and KELLER, M., 1992, *Visual Cues: Practical Data Visualization* (Los Alamitos, CA: IEEE Computer Society Press).

- KNAPP, L., 1995, A task analysis approach to the visualization of geographic data. In *Cognitive Aspects of Human-Computer Interaction for Geographic Information Systems*, edited by T. L. Nyerges (Dordrecht, Netherlands: Kluwer Academic Publishers), pp. 355–371.
- KRAAK, M.-J., and MACEACHREN, A. M., 1999, Visualization for exploration of spatial data (editorial introduction to special issue). *International Journal of Geographical Information Science*, **13**, 285–287.
- KRAEMER, K. L., and KING, J. L., 1988, Computer-based systems for cooperative work and group decision making. *ACM Computing Surveys*, **20**, 115–146.
- LIN, C., LOFTIN, R. B., and STARK, T., 1998, Virtual reality for geosciences visualization. In *Proceedings of Computer Human Interaction. 3rd Asia Pacific* (Los Alamitos, CA: IEEE), pp. 196–201.
- MACEACHREN, A. M., 1995, *How Maps Work: Representation, Visualization and Design* (New York: Guilford Press).
- MACEACHREN, A. M., 2000, Cartography and GIS: facilitating collaboration. *Progress in Human Geography*, **24**(3), 445–456.
- MACEACHREN, A. M., 2001, Cartography and GIS: Extending collaborative tools to support virtual teams. *Progress in Human Geography*, **25**, 431–444.
- MACEACHREN, A. M., in press, Moving geovisualization toward support for group work. In *Exploring Geovisualization*, edited by J. Dykes A. M. MacEachren and M.-J. Kraak (Amsterdam: Elsevier).
- MACEACHREN, A. M., BREWER, I., and STEINER, E., 2001, Geovisualization to mediate collaborative work: tools to support different-place knowledge construction and decision-making. In *Proceedings of 20th International Cartographic Conference* (Utrecht: International Cartographic Association), pp. 2533–2539.
- MACEACHREN, A. M., EDSALL, R., HAUG, D., BAXTER, R., OTTO, G., MASTERS, R., FUHRMANN, S., and QIAN, L., 1999, Virtual environments for geographic visualization: Potential and challenges. In *Proceedings of the ACM Workshop on New Paradigms in Information Visualization and Manipulation*, www.geovista.psu.edu/publications/NPIVM99/ammNPIVM.pdf, pp. 35–40.
- MACEACHREN, A. M., and KRAAK, M.-J., 1997, Exploratory cartographic visualization: advancing the agenda. *Computers & Geosciences*, **23**, 335–343.
- MACEACHREN, A. M., and KRAAK, M.-J., 2001, Research challenges in geovisualization. *Cartography and Geographical Information Science*, **28**, 3–12.
- MANDVIWALLA, M., and OLDMAN, L., 1994, What do groups need? A proposed set of generic groupware requirements. *ACM Transactions on Computer-Human Interaction*, **1**, 245–268.
- MARK, D., (editor), 1999, *NSF Workshop Report—Geographic Information Science: Critical Issues in an Emerging Cross-disciplinary Research Domain* (Washington, DC: NSF).
- MAY, R. A., 1999, *HI-SPACE: A Next Generation Workspace Environment*. Unpublished Masters Thesis, Washington State University, Pullman, WA.
- MCGEE, D. R., and COHEN, P. R., 2001, Creating tangible interfaces by augmenting physical objects with multimodal language. In *Proceedings of 9th International Conference on Human-Computer Interaction* (New York, NY: ACM Press), pp. 113–120.
- MCGEE, D. R., COHEN, P. R., and WU, L., 2000, Something from nothing: Augmenting a paper based work practice via multimodal interaction. In *Proceedings of the ACM Designing Augmented Reality Environments DARE 2000* (New York, NY: ACM Press), pp. 71–80.
- MCGEE, D. R., PAVEL, M., ADAMI, A., WANG, G., and COHEN, P. R., 2001, A visual modality for the augmentation of paper. In *Proceedings of the Workshop on Perceptive User Interfaces (PUI'01)* (New York, NY: ACM Press). <http://www.cs.ucsb.edu/conferences/PUI/PUIWorkshop/PUI-2001/a2.pdf>
- MCGRATH, J. E., 1984, *Groups: Interaction and performance* (Englewood Cliffs, NJ: Prentice-Hall).
- MESROBIAN, E. M. R., SHEK, E., NITTEL, S., LAROCHE, M., and KRIGUER, M., 1996, OASIS: an open architecture scientific information system. In *Proceedings of Sixth International Workshop on Research Issues in Data Engineering, 1996. Interoperability of Nontraditional Database Systems* (Los Alamitos, CA: IEEE Computer Society), pp. 107–116.

- MUNDA, G. P. N. P. R., 1994, Qualitative multicriteria evaluation for environmental management. *Ecological Economics*, **10**, 97–112.
- MUNTZ, R. R., BARCLAY, T., DOZIER, J., FALONTSOS, C., MACEACHREN, A. M., MARTIN, J. L., PANCAKE, C. M., and SATYANARAYAN, M., 2003, *IT Roadmap to a Geospatial Future* (Washington, D.C.: National Academies Press).
- NARDI, B., editor, 1996, *Context and Consciousness: Activity Theory and Human-Computer Interaction*. (Cambridge, Mass: MIT Press).
- NIELSEN, J., 1993, *Usability Engineering* (New York: Academic Press).
- NOLL, S., PAUL, C., PETERS, R., and SCHIFFNER, M., 1999, Autonomous agents in collaborative virtual environments. In *Proceedings. IEEE 8th International Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises (WET ICE '99)* (Los Alamitos, CA: IEEE Computer Society), pp.208–215.
- NYERGES, T., 1999, Progress in spatial decision making using geographic information systems. In *Geographic Information Research: Trans-Atlantic Perspectives*, edited by M. Craglia and H. Onsrud (London: Taylor & Francis), pp.129–142.
- NYERGES, T. L., MONTEJANO, R., OSHIRO, C., and DADSWELL, M., 1997, Group-based geographic information systems for transportation improvement site selection. *Transportation Research C*, **5**, 349–369.
- OLSON, G. M., ATKINS, D. E., CLAUER, R., FINHOLT, T. A., JAHANIAN, F., KILLEEN, T. L., PRAKASH, A., and WEYMOUTH, T., 1998, The upper atmosphere research collaboratory. *Interactions (May/June)*, 48–55.
- OLSON, G. M., and OLSON, J. S., 2000, Distance matters. *Human-Computer Interaction*, **15**, 139–178.
- OVIATT, S., ANGELI, A. D., and KUHN, K., 1997, Integration and synchronization of input modes during multimodal human-computer interaction. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI'97)* (New York, NY: ACM Press), pp.415–422.
- PADULA, M., and RINALDI, G. R., 1999, Mission critical web applications: A seismological case. *Interactions*, **July–August**, 52–66.
- PANG, A., and FERNANDEZ, D., 1995, REINAS instrumentation and visualization. In *Proceedings, OCEANS '95. MTS/IEEE. Challenges of Our Changing Global Environment* (Los Alamitos, CA: IEEE), pp.1892–1899.
- PANTELIDIS, V. S., 2000, *The RAVE, CAVE, and Collaborative Virtual Environments* (Greenville, North Carolina: <http://www.coe.ecu.edu/vr/rave/RAVetext.htm>).
- PARK, K. S., KAPOOR, A., and LEIGH, J., 2000, Lessons learned from employing multiple perspectives in a collaborative virtual environment for visualizing scientific data. In *Proceedings of the Third International Conference on Collaborative Virtual Environments* (New York, NY: ACM Press), pp.73–82.
- PATEL, U., D'CRUZ, M. J., and HOLTHAM, C., 1997, Collaborative design for virtual team collaboration: a case study of jostling on the web. In *Symposium on Designing Interactive Systems Proceedings of the conference on Designing interactive systems: processes, practices, methods, and techniques* (New York, NY: ACM Press), pp.289–300.
- PIERCE, C. S., 1955, Logic as semiotic: The theory of signs. In *Philisophical Writings of Pierce*, edited by H. Buchler (New York: Dover Publications), pp.98–119.
- PRATES, R. O., DE SOUZA, C. S., and GARCIA, A. C. B., 1997, A semiotic framework for multi-user interfaces. *SIGCHI Bulletin*, **29**, 28–39.
- QIAN, L., WACHOWICZ, M., PEUQUET, D., and MACEACHREN, A., 1997, Delineating operations for visualization and analysis of space-time data in GIS. *GIS/LIS '97* (Washington, D.C.: ACSM), pp.872–877.
- RAUSCHERT, I., AGRAWAL, P., FUHRMANN, S., BREWER, I., WANG, H., SHARMA, R., CAI, G., and MACEACHREN, A., 2002, Designing a human-centered, multimodal GIS interface to support emergency management. In *ACM GIS'02, 10th ACM Symposium on Advances in Geographic Information Systems* (New York, NY: ACM Press), pp.119–124.
- RHYNE, T.-M., 1998, Case study #1: Collaborative geographic visualization. *Course Notes: ACM SIGGRAPH '98, #35, Interactive visualization & web-based exploration in the physical and natural sciences*, Orlando, pp. www.education.siggraph.org/rhyne/vis-tut/gisvis-tut/casegisvis.html.

- RINNER, C., 1997, Discussing plans via the World-Wide Web. In *Proceedings of 15th ECAADE* (Vienna University of Technology: Osterreichischer Kunst- und Kulturverlag).
- RINNER, C., 1999, Argumaps for spatial planning. In *Proceedings of TeleGeo'99, First International Workshop on Telegeoprocessing* (Lyon, France: Claude Bernard University), pp. 95–102.
- RINNER, C., 2001, Argumentation maps: GIS-based discussion support for online planning. *Environment and Planning B-Planning & Design*, **28**, 847–863.
- ROSCELLE, J., and PEA, R. D., 2002, A walk on the wild side: How wireless handhelds may change CSCL. To be presented at *CSCL 2002: ACM Conference on Computer Supported Collaborative Learning* (Boulder, CO: University of Colorado), 10 pp. http://www.cs.colorado.edu/~13d/cscl2002/docs/CSCL2002_Proceedings.pdf
- ROSCELLE, J., and TEASLEY, S. D., 1995, The construction of shared knowledge in collaborative problem solving. In *Computer Supported Collaborative Learning*, edited by C. O'Malley (Berlin: Springer-Verlag), pp. 69–97.
- ROUSSOS, M., JOHNSON, A., MOHER, T., LEIGH, J., VASILAKIS, C., and BARNES, C., 1999, Learning and building together in an immersive virtual world. *Presence*, **8**, 247–263.
- SHIFFER, M. J., 1998, The evolution of public participation GIS. *Cartography and Geographic Information Systems*, **25**, 89–94.
- SHNEIDERMAN, B., 1998, *Designing the User Interface—Strategies for Effective Human-Computer Interaction*, Third edition (Reading: Addison-Wesley Longman).
- SHUM, S. J. B., MACLEAN, A., BELLOTTI, V. M. E., and HAMMOND, N. V., 1997, Graphical argumentation and design cognition. *Human-Computer Interaction*, **12**, 267–300.
- STAR, S. L., 1989, The structure of ill-structured solutions: Boundary objects and heterogeneous distributed problem solving. In *Readings in Distributed Artificial Intelligence*, edited by M. Huhns and L. Gasser, (Menlo Park, CA: Morgan Kaufmann), **2**, pp. 37–54.
- SZALAVÁRI, Z., ECHSTEIN, E., and GERVAUTZ, M., 1998, Collaborative gaming in augmented reality. In *Proceedings of VRST '98* (New York, NY: ACM Press), pp. 195–204.
- TAKATSUKA, M., and GAHEGAN, M., 2002, GeoVISTA Studio: A codeless visual programming environment for geoscientific data analysis and visualization. *Computers & Geosciences*, **28**, 1131–1144.
- TAYLOR, S. R. A., 2001, *Streaming Geospatial Imagery into Virtual Environments*. Unpublished PhD Dissertation, Australian National University.
- TROMP, J., BULLOCK, A., STEED, A., SADAGIC, A., SLATER, M., and FRÉCON, E., 1998, Small group behavior experiments in the Coven Project. *IEEE Computer Graphics & Applications*, **Nov/Dec**, 53–63.
- TUKEY, J. W., 1977, *Exploratory Data Analysis* (Reading, Mass: Addison-Wesley).
- VARIAN, H., ALLEN, F., BRYNJOLFSSON, E., SCHEMENT, J., SHENKER, S., SPROULL, L., and SUTCH, R., 1998, *Fostering Research on the Economic and Social Impacts of Information Technology: Report of a Workshop*. (Washington, DC: National Academy Press).
- WASSERMAN, S., and FAUST, K., 1994, *Social Network Analysis: Methods and Applications* (Cambridge, UK: Cambridge University Press).
- WATSON, V. R., 2001, Supporting scientific analysis within collaborative problem solving environments. *HICSS-34 Minitrack on Collaborative Problem Solving Environments* (Los Alamitos, CA: IEEE).
- WHELESS, G. H., LASCARA, C. M., VALLE-LEVINSON, A., BRUTZMAN, D. P., HIBBARD, W. L., PAUL, B., and SHERMAN, W., 1996, The Chesapeake Bay Virtual Ecosystem: Initial results from the prototypical system. *International Journal of Supercomputer Applications and High Performance Computing*, **10**, 199–210.
- WILBANKS, T., ADAMS, R., CHURCH, M., CLARK, W., DE SOUZA, A., GILMARTIN, P., GRAF, W., HARRINGTON, J., HORN, S., KATES, R., MACEACHREN, A., MURPHEY, A., RUSHTON, G., SHEPPARD, E., TURNER, B., and WILLMOTT, C., 1997, *Rediscovering Geography: New relevance for science and society* (Washington, DC: National Academy of Sciences).
- WOOD, J., WRIGHT, H., and BRODLIE, K., 1997, Collaborative visualization. *Proceedings, IEEE Information Visualization '97* (Los Alamitos, CA: IEEE Computer Society), pp. 253–259.
- XIANG, W. N., GROSS, M., FABOS, J. G., and MACDOUGALL, E. B., 1992, A fuzzy-group multicriteria decision making model and its application to land-use planning. *Environment and Planning B*, **19**, 61–84.