Available online at www.sciencedirect.com

SciVerse ScienceDirect

Int. J. Human-Computer Studies 71 (2013) 4–23

International Journal of Human-Computer Studies

www.elsevier.com/locate/ijhcs

# Supporting collaborative sense-making in emergency management through geo-visualization

Anna Wu, Gregorio Convertino, Craig Ganoe, John M. Carroll, Xiaolong (Luke) Zhang*

*Penn State University, State College, PA 16802, United States*

Received 21 January 2011; received in revised form 26 April 2012; accepted 16 July 2012
Available online 16 August 2012

**Abstract**

In emergency management, collaborative decision-making usually involves collaborative sense-making of diverse information by a group of experts from different knowledge domains, and needs better tools to analyze role-specific information, share and synthesize relevant information, and remain aware of the activities of others. This paper presents our research on the design of a collaborative sense-making system to support team work. We propose a multi-view, role-based design to help team members analyze geo-spatial information, share and integrate critical information, and monitor individual activities. Our design uses coordinated maps and activity visualization to aid decision-making as well as group activity awareness. The paper discusses design rationale, iterative design of visualization tools, prototype implementation, and system evaluation. Our work can potentially improve and extend collaborative tasks in emergency management.


*Keywords:* Computer-supported cooperative work; Geo-collaboration; Visualization; Collaborative sense-making; Web-based application

## 1. Introduction

Decision-making in complex task situations such as emergency management often requires the collection and analysis of various kinds of information. Such decision-making processes usually involve multiple domain experts, who can interpret and synthesize domain-specific information for the team. Our previous research on the process of knowledge sharing in emergency management teams in central Pennsylvania found that the teams engaged in heavy sense-making activities require collaborative work on geo-spatial information (Schafer et al., 2007, 2008). With a series of laboratory studies, we investigated how emergency management teams shared knowledge, and explored the design requirements and measurement of the effects of collaborative software tools to support knowledge sharing and decision-making (Convertino et al., 2008, 2009, 2011).

In many American communities emergency management is carried out by a *loosely* coordinated group of community organizations—volunteer fire companies, municipal police, partly-volunteer emergency medical technicians, and so forth. In our field work (Schafer et al., 2008) ''shadowed'' the emergency management coordinator for Central Pennsylvania for a year and found that coordination across these many groups is difficult—even in better-integrated local government and community groups. For example, the various groups usually meet face-to-face only 1–2 times per year, due to the constraints of their availability, to carry out table-top simulation exercises or full scale emergency walk-through. The purpose of these exercises is to develop, debug, refine, and practice regional emergency plans, so that various contributing organizations will be able to effectively coordinate in a real emergency and have a shared understanding upon which to base necessary improvisations that may be required in a real emergency.

In studying this activity, we found that there was significant plan recall failure. People just do not remember the plans very well through the many months during which they are not practicing or reviewing the plans. They do not have a good understanding of what others are doing within the plan, which could be an obstacle to effectively improvising on the

*Corresponding author. Tel.: +1 814 8639462; fax: +1 814 865 6426.
*E-mail address:* lzhang@ist.psu.edu (X. (Luke) Zhang).

1071-5819/$ - see front matter 
http://dx.doi.org/10.1016/j.ijhcs.2012.07.007

plan during a real emergency. In our terminology, they had rather low activity awareness (Carroll et al., 2003).

Through interaction with the regional emergency management coordinators of the teams, we have learned that it would be useful if the teams could have a persistent information system that (1) depicts the plans and allows actors to see their roles and activities relative to those of other actors and that allows them to annotate and discuss the plans; and (2) is accessible to all of the geographically-distributed participants and their organizations to overcome the constraints of distance and to have them involved in emergency management remotely and more frequently.

Consider the following decision-making scenario, which summarizes key aspects of collaboration in the emergency management teams that we studied:

*Three experts located in different cities are called in for an emergency management operation to find a solution for evacuating a family with special medical needs from a flooded area to a shelter. They are responsible for issues in different domains: a public-work expert to examine roads, bridges, and public infrastructures; an environmental-safety expert to monitor hazardous substances; and a medical expert to evaluate the medical situation of and needs by the family. They must find a shelter among four candidates so that the shelter can be reached safely by the family and has needed medical supplies. To work out a plan, each domain expert must gather and probe information in his/her own domain and share information critical to decision-making with others. Eventually, the team integrates inputs from all parties and determines the best shelter by considering the advantages and disadvantages of all shelters.*

*Maps are used heavily in collaboration for information synthesizing and sharing. For example, the public-work expert needs to mark all constraints on transportation on her own map, and then to circle those key viable roads on a public map so that her two collaborators can take this information into account in their planning. Because of the significant amount of information to be considered in planning, maps can get cluttered around the shelter locations, making it difficult for the experts to find what they need.*

As this scenario indicates, experts play domain-relevant roles in teamwork by sharing, analyzing, and synthesizing available information with their expertise. The scope of issues that affect the success of collaboration in emergency management and planning could be broad and span across various types of data, individual tasks, and group tasks, which go beyond what this role-based collaboration scenario can capture. However, empirical work (Schafer et al., 2007; Robinson, 2008) indicates that such role-based collaboration is not unusual in collaborative decision-making. Also, from the perspective of the analysis and integration of domain-specific information, such role-based scenarios offer substantial insight into key issues that should be considered in support-system design. Brodlie et al. (2005) used a similar scenario to illustrate the challenges that collaborative geovisualization systems should address.

In support of collaboration tasks described by the scenarios, we need systems that can help collaborators deal with various challenges that may impede information sharing and activity coordination. Our work aims at augmenting the abilities of individual decision-makers with tools to support collaborative information sharing, discussion, and sense-making. The goal is to take advantage of the strengths of human agents in recognizing patterns, making abstractions, and assessing ill-defined situations, combined with the strengths of computational tools in processing, storing, and retrieving large amounts of information. We propose a multi-view, role-based design approach that uses coordinated maps and activity visualization to aid information sharing and integration. We focus on the design of collaborative sense-making support for decision-making involving the analysis of geo-spatial information by multiple domain experts. We describe an iterative design process of a system to support geo-Collaboration with Information VIsuaLization (CIVIL). The system provides visualization tools to facilitate information sharing, sense-making, and decision-making in small emergency management teams that consist of domain experts.

This paper presents design solutions for the activity awareness problem by supporting collaborative sense-making in distributed group emergency management. The paper first reviews relevant research work in the areas of computer-supported cooperative work (CSCW), geo-collaboration, and information visualization. Then, it discusses key needs for geo-collaboration in emergency management and proposes design rationales. Next, it describes an iterative design process that includes system prototype implementation, system evaluation, and system improvement. Finally, the paper concludes with discussions and implications of our results and future research directions.

## 2. Related work

Our work stands between CSCW field and visualization technology to support geospatial decision-making. In this section, we review the related work in these areas.

### 2.1. CSCW, group decision-making, and sense-making

The cognitive resource involved in group collaboration is not the mere sum of individual intelligence. MacMillan et al. (2004), p. 61observe that team cognition is different from individual cognition because it requires communication, which is "a process that has no direct analog in individual cognition". Additional cognitive resources must be invested to communicate. The relation between the process of communication and the way collaborative visualizations can support this process is a key research issue. Team communication can be facilitated through channels of communication in which participants' actions relative to task- relevant objects is public (McCarthy et al., 1991). This suggests that collaborative visualization – such as deictic expressions like "this," "there," and "it" – may be made visible and public through the use of telepointers, pen tools, or annotation tools.

The distinction between personal and shared spaces has been indicated as a useful feature of workspaces for people who work with artifacts in collaboration. When Greenberg et al. (1999) investigated how people moved their personal artifacts into the public domain and back again, they argued that the use of automatic publication may be inappropriate because it denies individuals the opportunity to express personal relevancy, and discourages people from using the tool to develop ideas not yet ready for dissemination. The results of a study on annotation sharing (Marshall and Brush, 2002) show that when transferred from personal to shared workspace people's annotations undergo habitual filtering or publishing operations (e.g., clarifications). This suggests that the same information tends to satisfy different functions depending on whether it is presented privately (e.g., to aid memory) or publicly (e.g., to aid communication).

Unsupported individuals and groups are both limited and biased when they need to use large and dynamic information corpora to make decisions under uncertain conditions. We isolate three main systematic limitations or biases that affect groups' ability to accurately share knowledge and make decisions.

1. Groups' biased analysis and discussion: when sharing and discussing both shared and unshared information, collaborators tend to favor familiar information over unfamiliar information. Unless corrective interventions are introduced, group discussions are systematically biased toward shared information at the expense of unshared and less familiar information (see hidden profile in Stasser and Titus, 2003).
2. Limited information processing capacity: collaborators have both a limited capacity to process massive amounts of information in a short interval of time and a limited ability to accurately distinguish and manage distinct epistemological categories of information at the same time: facts and sources, inferences about facts and sources, how-to knowledge about the task, experts' related experience (e.g., Tversky and Kahneman, 1974).
3. Groups' biased synthesis and decisions: when interpreting the meaning and weighing the relevance of information under uncertainty and social influence, a group make decisions under the influence of systematic biases such as anchoring to early hypotheses and bias in posterior-probability estimates (e.g., Convertino et al., 2008).

Decision-making often involves sense-making activities. Sense-making is a key component of knowledge work, and occurs when people face new problems or unfamiliar situations and their knowledge is insufficient for the task. Sense-making finds critical patterns in a seemingly unstructured situation by developing successively more sophisticated representations and fitting information into these representations in service of a task (Russell et al., 1993). Traditional theories of sense-making have tended to be either purely top-down or bottom-up. Top-down approaches emphasize the necessity of using proper representations in sense-making (Russell et al., 1993; Qu and Furnas, 2005). A representation usually refers to a diagrammatic (e.g., trees, graphs), pictorial, or narrative description of a data relationship. An appropriate representation is necessary to guide such sense-making activities as searching and integrating information. Bottom-up approaches de-emphasize the role of a priori representations in guiding sense-making, and adopt a "from data to wisdom" method focused on information exploration and inductive construction of knowledge schemata (Ackoff, 1989). The strength of bottom-up approaches is in the potential for new insights and discoveries of structures and relationships in data. Recently, researchers have proposed hybrid approaches for sense-making as a process involving both finding appropriate representations to suit given structures and developing structures based on available information (Bodnar, 2005; Pirolli et al., 2005; Pirolli and Card, 2005; Klein et al., 2006). However, some questions remain, including how to connect top-down and bottom-up activities.

Sense-making also exists in group activities and researchers have called for new designs to support collaborative sense-making because of its importance to group activities. Research has shown that group sense-making often involves a team of people who analyze, share, and synthesize relevant information together (Schafer et al., 2008; Robinson, 2008). Paul et al. (2008) argue the need for flexible representation where tools are switched to address the gaps in sense-making between individuals and groups. Qu and Hansen (2008) suggest that shared representations among group members are important to collaborative sense-making.

### 2.2. Awareness in distributed groups

Awareness in computer-mediated groups is an issue that has been extensively researched. Generally speaking, awareness is about the knowledge of others in a group, which can help better understand the group activities and improve group performances (Dourish and Bellotti, 1992). Awareness information concerns different perspective of group behaviors, such as presence awareness (Curry, 1999; Slater et al., 1992), which is about whether a person is available in workspace, and activity awareness (Carroll et al., 2003), which emphasizes the importance of understanding activity context in situations beyond face-to-face situations.

Our interest here is in activity awareness. The term "activity" refers to "substantial and coherent collective endeavors directed at meaningful objectives'' and the ''activity awareness'' as ''the sharing requirement'' (Carroll et al., 2003). With this definition, a team formed of multiple stakeholders with different responsibilities need to know what others are doing and how they are doing to succeed in their coordination. In coordination tasks, team members often need to share and manipulate resources (human power, natural resources, time etc.). Knowing the availability of required resources and who is dealing with such resources is important as well. Knowledge of other people's interaction with object in the shared workspace is defined as action awareness, which is widely supported in synchronized collaboration (e.g., radar views, telepointers).

The idea to support high-level activity awareness provides design opportunities in taking advantage of mediated technology for distributed collaboration. Carroll et al. (2006) have identified potential techniques to support activity awareness from four aspects: common ground (e.g., radar view, media space), communities of practice (e.g., annotation, discussion board), social capital (e.g., activity log visualization, resource usage indicators), and human development (e.g., historical view of personal profile, annotated workflow). Carroll et al. (2003) demonstrated an early effort in support activity awareness in virtual classroom through situation, group, task, and tool factors.

### 2.3. Supporting geo-collaboration with visualization

Generally speaking, information visualization can support decision-making (Card et al., 1999) by increasing the memory and process resource available to users and by using visual representations to enhance pattern detection. In case of geo-collaboration, maps offer additional help for group activities. In this section, we first review literature on using conventional information visualization techniques to support sense-making and group decision-making. Then, we examine visualization techniques for specific roles with the use of maps, or geo-visualization, in supporting group activities.

#### 2.3.1. Information visualization to support sense-making and group decision-making

Weick and Meader (1993) called for ''sense-making support systems'' to construct consensual definitions for building common understanding. Visualization has been used to achieve this goal. DiBiase (1990) distinguished two purposes of visual artifacts – assisting visual thinking in the private domain and facilitating visual communication in the public domain – and indicated the important role of visualization tools as a medium to enhance group communication. Studies in the military sector have shown that visualization techniques can help people to rapidly comprehend complexly tangled information in emergency situations (Feibush et al., 2000). Recently, Bier et al. (2008) presented a system to facilitate the discovery and organization of relevant information in collaborative intelligent analysis; other systems aimed specifically at increasing the quality of the group reasoning by reducing judgment bias in these collaborative conditions (Convertino et al., 2008).

The presence of visualization also can influence the level of participation of the members and the information sharing process during group decision-making. Studies of computer-supported communities have shown that member participation or community development can be influenced using appropriate tools (Beenen et al., 2004). Shared visualizations can help collocated working groups to communicate more effectively by externalizing the communication process (DiMicco et al., 2003).

Although visualization is regarded as a powerful tool for group sense-making, most existing visualization systems largely focus on visualizing artifacts and content for the tasks. There is still very limited support for visualizing relevant aspects of the work process in order to enhance the awareness and sense-making abilities of groups.

#### 2.3.2. Geo-visualization to support group decision-making

Maps have been used in various professions for a very long time in problem solving and decision-making by providing visual representations of geographic space (MacEachren, 1995). However, the functions of maps have been dramatically expanded in modern times. Nowadays, maps are regarded as artifacts that facilitate complex human activities involving the use, access, and organization of geo-spatial information (MacEachren and Kraak, 2001). Research in psychology also has found that maps are cognitive artifacts that can help individuals by extending their memory and easing information processing (Tversky, 2000). As shared means for group tasks, they can help collaborators to jointly focus attention and communicate more effectively (e.g., Heiser et al., 2004; Clark and Krych, 2004).

Geo-visualization, a new discipline that emerged from the Geographic Information Science (GIScience) field, goes beyond simple graphic representations of geo-spatial information, which is the focus of cartography, and considers broader issues such as the integration of knowledge construction with geo-spatial information, user interface design, and cognitive challenges in perceiving and processing geo-spatial information (MacEachren and Kraak, 2001).

Recent advances in computer graphics, computer networks, collaborative software, and Web-based technology (e.g., Google Maps and Yahoo! Maps) have triggered a digital revolution in the use of maps in many aspects of human life. In this context, researchers argue that the scope of issues that geo-visualization addresses should be further extended to support advanced analytical tasks. Kraak (2006) calls for research on how to use maps to encourage knowledge exploration and stimulate new ideas and analysis. Andrienko and Andrienko (2006) indicate that computer-based geo-visual analytical tools become important to spatial decision-making activities, and identify key issues associated with geo-visual analytics, including the exploration of problems and solutions, the integration of heterogeneous information, reasoning, deliberation, communication among stakeholders, and so on.

Geo-visualization is important to group decision-making in many ways. From the perspective of cartographic representation, maps can facilitate group discussion by offering cartographic objects to talk about, objects to think about, and objects used for action coordination (MacEachren and Cai, 2006). Maps also can serve as visual mediation and event context to help group members to understand a task. For example, Armstrong and Densham (1995) showed that different map types can help people compare alternative solutions to the same problem; research by Rinner (2001, 2006) showed that by explicitly linking arguments in a discussion with related geographic objects, argumentation maps can improve the analysis and summarization of current status in conversations and assist people completing geospatial related planning tasks.

Research efforts also have been made to investigate the design of geo-visualization systems for group activities. Brodlie et al. (2005) argue that distributed geo-visualization systems must consider the integration of three important factors: data, people, and computational resources. From the aspect of information sharing in group, Brodlie (2005) offers various models on collaborative visualization that can be applied in the design of different kinds of systems. Fuhrmann and Pike (2005) outline a set of user-centered design approaches for collaborative geo-visualization tools.

In summary, sharing, synthesizing, and making sense of geo-spatial and non-geo-spatial information are critical to collaborative decision-making in emergency management and planning. Conventional Geographic Information Systems (GIS) (e.g., ArcGIS) and map services (e.g., online digital maps) are insufficient to support such collaborative activities because they are usually designed for individual users (MacEachren and Brewer, 2004). The gap between these GIS tools and the need for geo-collaboration has been identified by some researchers (Cai, 2005). Research efforts have been made to explore new theoretical understandings of collaborative geo-visualization (Brodlie et al., 2005; MacEachren, 2005; Brodlie, 2005) and new designs to support collaborative geo-visualization (Kemp, 2005; Fuhrmann and Pike, 2005). However, most of these efforts are targeted for generic models or high-level design issues that are insufficient to handle the complex activities in geo-collaboration we observed in emergency management and planning.

## 3. Design rationale

Our design rationale was based on a previous field study (Schafer et al., 2007). This study focused on emergency management activities in central Pennsylvania, and summarized key software requirements for geo-collaboration decision-making in emergency management. In this section, we briefly present the fieldwork and design requirements, and then discuss the design of our geo-collaboration system.

The fieldwork studied two communities in the central Pennsylvania, observing emergency management practice. In the study, local emergency management coordinators were interviewed about their planning activities, and archival data (e.g., meeting minutes and e-mail records among team members) were collected. Some emergency planning meetings were audio-recorded, transcribed, and analyzed.

The study developed a set of software design requirements to support emergency response planning activities. More importantly, the study informed the design of two lab experiments on decision-making processes in geo-collaboration (Convertino et al., 2008, 2009, 2011). Both the field study and lab work identified key sense-making processes performed by the work groups and suggested the need for better tools to support both their top-down and bottom-up sense-making activities.

### *3.1. Tools to support bottom-up (data-driven) activities*

Bottom-up activities usually focus on exploring new data. Such data exploration activities are largely conducted on maps. Maps are effective organizers of geospatial data. Moreover, when shared in a group, they allow referencing of shared objects while the members discuss and plan together (i.e., deixis). Our system design introduced multiple, role-based views coordinated with a team view. As a result, in our laboratory studies, each group member used two maps for data exploration: one personal map with role-specific data for individual analysis and one shared map for the team to share information and build a group plan. With these maps, the individuals could conduct the following activities:

- **Exploring geographic locations.** To make a good emergency management plan, team members need to be able to explore and understand the focus areas and surrounding areas. Such exploration could be conducted by either individual planners or by a team. For example, finding a route to evacuate people from an emergency requires planners to know and explore road systems in the area as well as in neighboring areas. Planners can either gather such information individually or as a team.
- **Labeling and annotating geographic locations.** In collaboration, planners often need to add important information related to certain locations. They may sketch on map locations or write down comments. Added information can be role-specific or shared within the team. Thus, tools to support individual and collaborative sketching and annotation on maps should be provided.

### *3.2. Tools to support top-down (representation-driven) activities*

Top-down activities are guided by certain knowledge representation. Often, people use representation tools to externalize critical information and knowledge, such as what activities individuals performed, what information was involved in discussions, what decision has been reached, and so on. Thus, tools are needed to support:

- **Clustering and aggregation of information contents.** The field study (Schafer et al., 2007) shows that collaborative sense-making often involves the integration of relevant information from different sources. It is important to give sense-makers tools to cluster and aggregate inputs from individuals. Tools like sorting tables and histogram charts should be provided for information review and analysis.
- **Representation of activity data.** Activity awareness is critical to group work (Carroll et al., 2003). Team members should know what work individuals have done, when they did that work, where their contributions were, and so on. Timeline tools should be provided for such activity awareness. The granularity of timelines can be changed, and if so, sense-makers can cluster and aggregate activities based on different activity attributes (e.g., location) (Zhang et al., 2010) and action types (Gotz and Zhou, 2009).

The above design requirements lead to the following design considerations for a geo-collaboration supporting system in emergency management.

### *3.3. Map-centric collaboration support*

Geo-collaboration often involves large amount of geospatial information. It would be desirable to have artifacts to externalize geospatial information so that collaborators can easily refer to common geospatial objects in discussions and planning.

### *3.4. Annotation and sketching support*

Maps are often designed for general purposes. With maps, paper-based or digital, users can obtain geospatial information and common tools that map designers or systems have prepared for general public. Using maps in collaboration, individuals may need to express their personal perspectives or opinions, which are usually related to objects on maps. To make such individual information reviewable for future discussions, tools are needed to record the information. Individual users should have tools to take notes of the ideas that occur to them, compare the advantages and disadvantages of specific options in discussions, and add comments on spatial objects. Individuals also should have sketching tools to illustrate spatial relationships among objects of interest, and to mark where issues may reside.

While annotation and sketching tools have been widely used to help individuals analyze complex information (Fernandes et al., 1997), they also are important to group collaboration by facilitating group activities. For example, Tversky (2000) argues that tools like sketching allow people to depict their internal understanding of the external world in social interaction.

### *3.5. Awareness support*

In collaboration, it is important to provide users with awareness information, i.e., to let them know who is collaborating and what others are doing (Dourish and Bellotti, 1992). In collaboration that heavily involves information and knowledge exchange among domain experts, awareness becomes even more important to prompt information and knowledge sharing without forcing team members to strategize the work overtly. The aim is to create the conditions for seamlessly sharing knowledge and coordinating action at low cost.

For a geo-collaboration team with domain experts, supporting such ‘‘implicit coordination’’ (Kleinman and Serfaty, 1989) requires tools to help collaborators access various indications of members’ roles and their actions. For example, team members and information artifacts associated with them (e.g., comments and sketches) can be color-coded to help others recognize individual contributions. Telepointers (Greenberg et al., 1996) can be provided so that team members know where a teammate is focusing and what that teammate is doing.

### *3.6. Multiple map views to support both personal and shared activities*

In geo-collaboration, where maps are the central artifact for collaborative activities, having both a personal or role-specific map view as well as a shared or team map view is important. Prior research has suggested that providing team members with a personal workspace improves the quality of collaboration (Olson et al., 1992) because personal workspace allows individuals to perform role-specific activities that they do not want to share with others. The availability of a shared view among collaborators who work on problem solving tasks improves their communication efficiency (i.e., management of content) (Clark and Krych, 2004; Heiser et al., 2004) and helps them to build task structure knowledge and situation awareness (i.e., useful to managing the process) (Kraut et al., 2002).

It is also important to consider, in this context, that when experts work on complex problems under real conditions, they regularly experience information overload in managing both role-specific and shared information. Therefore, they need adequate support to filter out irrelevant information. We argue that the availability of distinct views for role-specific and shared information can help each team member to ‘‘selectively’’ share with teammates their role-specific (or unique) content, thus limiting their cognitive load while at the same time offering a personal space for individual analysis (Convertino et al., 2008, 2009, 2011). In fact, in our design, personal (role-specific) and shared (team) map views serve different purposes. The personal map view displays role-specific information and allows individuals to analyze their own data privately and explore various options before they decide what information and knowledge to share with others. At a team level, with different role-specific views used at the same time, the team members can execute data analysis and exploration in parallel, making collaboration more efficient. The team (shared) map, as the common view of all team members, is the place where shared information is displayed and where commonly-relevant objects and places are examined collectively. Information in the personal (role-specific) workspace often needs to be transferred to the shared space. Thus, the capacity to transfer information from role-specific maps to shared ones should be provided.

The technique of using multiple views already has been proven useful in helping individuals make sense of complex data sets (Roberts, 1998; Baldonado et al., 2000). However, this technique has been largely used in the context of single-user applications to address issues like the balance between context and content information (North and Shneiderman (2000)). More recently, research on collaborative systems has pointed to new needs to be accounted for in the design of collaborative applications: the need to manage large and heterogeneous knowledge sets, different professional roles, distinct role-specific and shared data and workspaces, and support for a sufficient level of mutual awareness among collaborators (see Convertino et al., 2005, for a more detailed review).

### 3.7. *Coordinated views to support sense-making and awareness*

To help team collaboration, information artifacts in multiple views also need to be coordinated. Team members may contribute to the teamwork by offering new annotations and creating new sketches. These new objects can appear in different views, such as in the public map as well as in the team action timeline, each of which serves different purposes (see prior section). To better understand and judge the contributions to teamwork by individuals, people need to understand how objects in different views are related (e.g., knowing which place an annotation is about in the public map and when the annotation was posted in the team action timeline). Using techniques such as color-coding or a dual-pointer to coordinate information artifacts in different views can help people connect objects of interest and understand the actions of team members.

It should be noted that multiple coordinated views have already been used to support information analysis. For example, Roth and his colleagues have proposed designs like SageTools (Roth et al., 1995) and Visage (Lucas and Roth, 1996) to use multiple views to support information exploration and analysis by individuals. Our use of multiple coordinated views focuses more on supporting group activities, such as sharing selective information within a group, enforcing specific roles that team members assume, and improving activity awareness (Convertino et al., 2005). The Command Post of the Future is a real multiple-view system developed by General Dynamics (http://www.gdc4.com) to support teams of U.S. military commanders in maintaining real-time situational awareness and coordinating operations in the battlefield (the system was deployed in the Iraq and Afghanistan wars). The coordinated views include shared interactive maps populated with data and coordinated with graphical and text-based views (Thomas and Cook, 2005). Different from our design, this system does not include role-specific views of the map, as distinct from and coordinated with the shared team view.

## 4. Design, implementation, and evaluation of system prototypes

Based on the above design considerations, we developed system prototypes to support role-based geo-collaboration. These system prototypes are targeted at multi-expert teams making complex decisions based on maps. The design and implementation of system prototypes went through a two-phased iterative process that included technical system implementation, system evaluation, and system function improvement.

### 4.1. *Phase I: Java system prototype*

The first system prototype was a Java application. We chose the Java technology because of its platform independence, which allows broader distributed collaboration, and the availability of geospatial information tools, which are critical to geo-collaboration support functions. Below, we briefly present the final version of the system and its evaluation in the field and the lab. See Carroll et al. (2007) for details on earlier versions of this prototype, and Convertino et al. (2008, 2009, 2011) and Convertino and Carroll (2011) about the lab evaluation studies. This work in Phase I is summarized here because it was foundational for the design work that followed in Phase II (Section 4.2).

#### 4.1.1. *Architecture*

The system architecture of our Java application is shown in Fig. 1. This architecture was designed to facilitate independent management of geographic data content and awareness content, the coordination of multiple map views, and the integration of interactive tools with multiple views and geographic data.

*4.1.1.1. Server layer.* This layer provides basic services for data storage and data communication among client applications. Two software packages are included in this layer: CORK (content object replication kit) and GeoTools. CORK is a Java toolkit developed to support the replication and manipulation of shared objects in both synchronous and asynchronous collaboration (Isenhour

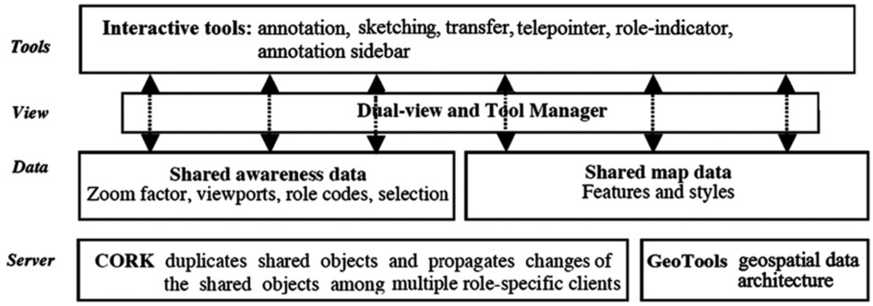


Fig. 1. System architecture of Java prototype.

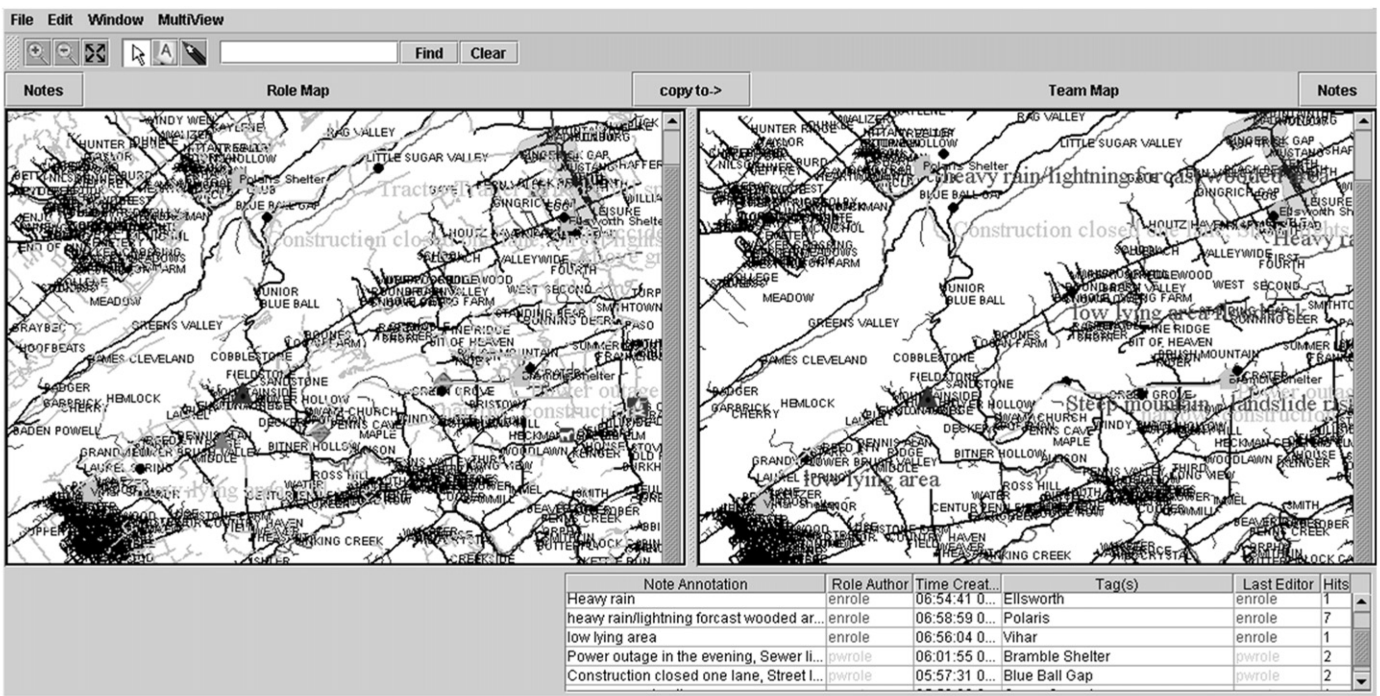


Fig. 2. User interface of Java prototype.

et al., 2001). GeoTools is an open-source Java library for the organization and manipulation of geospatial data (http://geotools.codehaus.org).

4.1.1.2. *Data layer.* By combining CORK and GeoTools, we provided data services to support group awareness and shared maps at this layer. We extended GeoTools objects with the CORK toolkit to support synchronously sharing changes of objects and group awareness. This layer has two components: a module for shared awareness data and a module for shared map data. While the former primarily manages data associated users, such as their roles and their actions, the latter manages data related to geospatial information and features, such as map locations and map scales.

4.1.1.3. *View layer.* Above the data layer sits the view layer that connects the high-level interactive tools with low-level data. It provides support for the management of two views and regulates what objects should be displayed in each view and what tools can be used in each view.

4.1.1.4. *Tools layer.* A set of tools to support geo-collaboration were implemented. We provided an annotation tool to add comments and a sketching tool to draw graphs on both personal (role-specific) and shared (team) maps. Annotations and sketches can be copied and transferred between the two maps. To support group awareness, a telepointer was used to show the cursor locations of other users, and the role indication tool coordinates the appearances (e.g., color) of information objects so that they are consistent with the users, i.e., roles, which they are associated with. An annotation sidebar is used to aggregate all shared annotations.

### 4.1.2. *User interface*

Fig. 2 shows the user interface of the system prototype. The user interface features a public map for team collaboration (on the right) and a role-specific map (on the left).

Each map displays multiple layers of geographical data. Each user's public map has the same set of information, but information on a user's personal map is not shared with others. Users can choose different tools (e.g., zooming and panning maps, adding annotations, sketching) by either clicking tool icons organized in tool bars, or selecting menu items.

The prototype also provided a sorting table to display all shared annotations. The table lists important attributes of each annotation item, including content, creator, the time the item was created, geographic location associated, person who made the most recent change, and times being reviewed. By clicking on a table column the user can re-sort all annotations.

#### *4.1.3. System evaluation*

In this research, we systematically integrated field and lab methods to evaluate the prototype. The fieldwork with real experts ensured validity and relevance to the real world. The lab studies, meanwhile, enabled us to perform controlled experimentation with the proposed design (for details, see Convertino and Carroll, 2011).

We conducted field work and a focus-group interview study in which we demonstrated the system to an emergency management team in central Pennsylvania and collected feedback about the overall design concept and various tools. The field work was important because only emergency management professionals can provide accurate feedback regarding whether our high-level design is appropriate to the real-world practice.

Asking emergency management professionals to participate in lab studies always presents many challenges, considering the limited availability of these individuals and their small number. Therefore, we modeled the work conditions and designed the tasks in the lab based on our field observations and with the help of experts (see Schafer et al., 2007) and ran a lab study with university students from campus. The lab study was necessary because it allows us to accurately measure the use of designed tools by controlling the user task and the use of tools, reducing the potential impacts of other factors on user behaviors.

*4.1.3.1. Fieldwork.* We demonstrated our system to the emergency management team and presented the major features of the system. The team expressed interest in our design. The map-centric, role-based approach was regarded as very valuable and suitable for their needs and practice in real-world planning sessions. In particular, interactive maps were welcomed by the team. Compared with paper maps they had used in the real-world practice, the digital maps offered the team more freedom in exploring and interpreting geo-spatial information.

While the team members showed enthusiasm about the overall design concept, their attitude toward the technology was reserved. The client-server architecture offered some benefits to the team by allowing individuals to work in a more distributed manner and balance role-specific and collaborative activities. However, through the discussions with the team, we found several issues that could potentially prevent our system from being used successfully. These issues were concerned with the technical constraints of installing, maintaining, and using the system. First, our prototype requires the management and maintenance of two key modules, CORK and GeoTools. Second, to create new training scenarios on new geographic locations, we had to add more geospatial data into the GeoTools. This is because the GeoTools is not a GIS system containing real data; rather it is just a toolkit to process geospatial data provided by users. The team, only including emergency management professionals, lacked the technical know-how to address these concerns.

*4.1.3.2. Lab evaluation.* The purpose of the lab study was to investigate the impact of our system on collaboration. In particular, we were interested in knowing how our visualization tools may facilitate the outcomes and processes of collaborative decision-making.

*4.1.3.2.1. Experiment design.* Existing research shows that proper deployment of geo-visualization tools can facilitate spatio-temporal analytics in dynamic situations (e.g., Andrienko and Andrienko, 2006). In tasks like emergency management and planning, maps can become "visual index" used for various tasks, including constructing heuristic knowledge, ordering decision option, and arguing outcome between different stakeholders (Jankowski and Nyerges, 2001). Our experiment was aligned with this view of the role of technology in group decision.

The experiment was a between-subject design. The independent variables were the way in which collaboration was conducted and technologies were involved. Two treatments were selected. One treatment was a face-to-face setup (FTF), in which team members worked together in a collocated environment and with paper-based maps. The other treatment was a software environment (SW), in which individual team members were put into different rooms and collaborated with each other by using our system prototype.

*4.1.3.2.2. Participants.* In total, ninety-six participants were recruited for the experiment from Pennsylvania State University. Twelve of the participants were university employees, and the rest were students. Their ages ranged from 20 to 45. The participants had little prior experience with emergency response planning or operations.

The participants were grouped into thirty-two three-person teams. To encourage equal participation and avoid male dominance (Herring, 1993), we created same-gender groups (except in one case). In the FTF treatment, we had six male teams, five female teams, and one mixed-gender team with one female and two males. In the SW treatment, we had ten male teams and ten female teams.

*4.1.3.2.3. Team task.* The experimental task was to construct a plan to evacuate a family in an imaginary emergency situation, similar to the collaborative decision-making scenario described in the beginning of this paper. Each team was asked to generate the best plan to move a family from a flooded area to an appropriate shelter. Each team member was assigned to one of three expert roles (public-work expert, environmental-safety expert, or medical expert). Since the participants were not actual experts, we had to provide each participant with a detailed description of the role he or she was to assume along with necessary role-specific background information. At the same time, we gave the participant the following information for the task: role-specific maps, information sheets with role-specific and shared information, and a shared task scenario with background information.

Each team performed three task runs, developing plans for three different task scenarios of the same type. The three task scenarios were similar in that each involved a family which needed to be rescued and four possible locations in which the family could be sheltered. Among these four shelters, only one was optimal. Each scenario was of equivalent complexity and the order was counterbalanced across the teams. Over the three repeated runs, or task scenarios, each member kept the same role.

Working as a team, the participants needed to integrate and synthesize information among themselves to reach the best solution. Each team member was provided with information about individual shelters, but that information was biased toward a non-optimal shelter. The team needed to compare the problems of each shelter (e.g., road condition to a shelter, medical equipment availability) based on information provided by individual team members, and then to choose the least problematic shelter.

This task was developed from an actual tabletop exercise observed in the field with real emergency management teams (see Schafer et al., 2007) and confirmed by the emergency management team in our fieldwork.

*4.1.3.2.4. Apparatus and lab setting.* In the FTF treatment, each team was put in a room in which three tables at right angles to one another so that each participant could have a dedicated working area with a role-specific map. At the same time, all team members could access a common area for group work with a team map. Participants could use colored post-its and colored pens to post notes on their own map and on the team map. Fig. 3 illustrates the aerial view of the table setup. The layout of three tables allowed three team members to examine their own maps and information sheet and at the same time to collaborate on the team map.

In the SW treatment, participants in a team were put into three different rooms. Each room was equipped with a Dell Optiplex workstation and a 19-inch widescreen LCD. Participants communicated verbally through a microphone and speakers on their workstations and collaborated through our prototype system, which was running on their workstations.

*4.1.3.2.5. Procedure.* Participants first signed an informed consent form and were asked to complete an online background questionnaire. After being presented a short

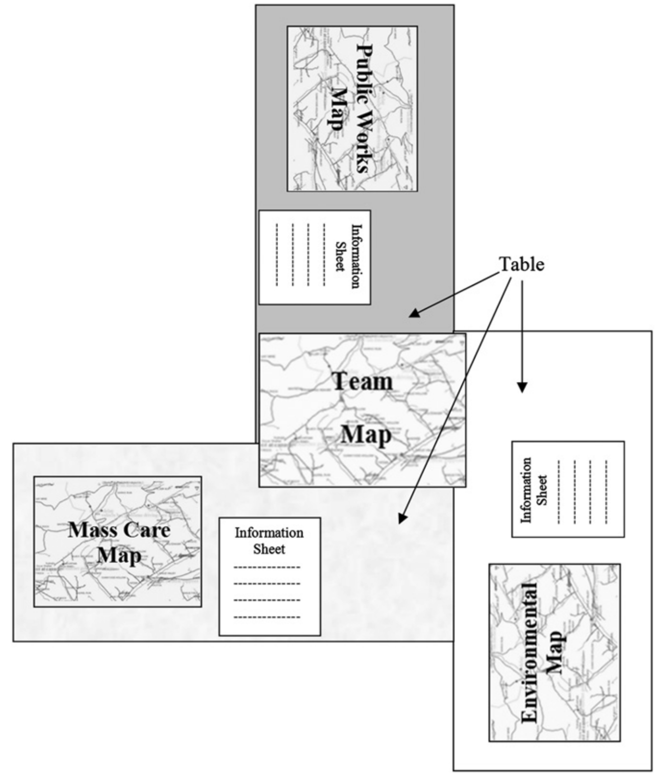


Fig. 3. An aerial view of the experimental setting in the FTF treatment.

introduction to the emergency planning problems, participants were given ten minutes to read descriptions of their individual roles and the shared task scenario and another three minutes to complete a role manipulation check to verify their understanding of their task and roles.

Then, the participants began to collaborate on the planning task. They were instructed to share information with the team through the shared map. When they reached a decision, they wrote down the final plan along with three alternatives in order of preference in a final plan document. Teams were told to try their best to finish a task scenario within twenty minutes, although we did not enforce the cut-off time. Teams decided whether a task was completed or not.

The participants in the SW treatments were asked to complete a standard usability questionnaire (see Appendix) to evaluate the software system from the aspects of overall system quality, information quality, and user interface quality. The questionnaire was extended to include a few open-ended questions on the prototype and its components (role-specific and shared maps), so that the participants could evaluate positive and negative aspects of the current design.

*4.1.3.2.6. Results.* Team interaction was recorded in both treatments. In the FTF treatment, we video-recorded the members' interactions on the maps (around a tabletop), and we analyzed the task artifacts generated. In the SW treatment, we video-recorded each member, we analyzed their artifacts, and we also used a screen-capture software to observe (as video-recording and keystrokes logs) each member's interaction with the software and with his or her collaborators. The recorded videos from each team were transcribed and coded for data analysis.

The resulting data allowed us to conduct an in-depth analysis about group collaboration. Other publications (Convertino et al., 2008, 2009, 2011) of ours provided more detailed results about group activities, such as performance, communication structures, the perception of group processes and performance, and the retention of task-relevant information. Here, we report results related to group information sharing, group performance, and user feedback on the overall user interface.

*Increased Content Sharing when Using Software*: We found that our prototype system encourages more efficient sharing of information content. We first compared the percentage of both "push" acts (adding information) and "pull" acts (replying to questions) in interactions among FTF and SW team members. We conducted this comparison because existing studies of common ground and media for communication have shown that changes in the proportion of some categories of dialog acts, such as querying acts, are associated with changes in the media and setting conditions for building common ground. For example, Clark and Brennan (1991) argued that extra dialogues within a group are often needed when the medium the group rely on provides comparatively less support for common ground building. Some research (O'Conaill and Whittaker, 1997; Sanford et al., 2004) has observed that the distributions of "align" and "query" acts in groups can vary from group to group, depending on their communicating technologies.

Our data showed that the SW teams used a greater proportion of push acts (10.9%) than the FTF teams did (8.5%), and a smaller proportion of pull acts (3.0%) than the FTF team (4.4%). We used a semi-parametric version of the Poisson regression model (Agresti, 2002) to test the effect of the collaboration setting (FTF vs. SW) on the proportions of push and pull acts. For the push acts, we found that the difference between two treatments approaches significance ($\beta = .26(0.15)$, $p < .08$). For the pull acts, the difference is significant ($\beta = -.81(0.15)$, $p < .001$). This result suggests that the team members shared information more efficiently when they worked remotely through our interactive prototype, compared to those who worked face-to-face using physical maps.

We further compared the percentage of push and pull acts between the first and the third task scenarios in the SW treatment. We found an increment of the proportion of push acts, from 9.5% to 12.2%, and a decrement of the pull acts, from 3.7% to 2.3%). The increment of push acts is significant ($\beta = .12(0.06)$, $p < .05$), while the decrement of pull acts is nearly significant ($\beta = .11(0.06)$, $p < .06$). This result suggests that the support provided by the software not only offset the cost of working remotely, but also favored a faster growth in the efficiency of content sharing over the repeated task runs. In fact, over time the teams began to push relevant information directly into the discussion rather than waiting for a request, which makes the content sharing process more efficient: i.e., a push act (adding information) replaced two or more request and response acts. Also, this improvement in efficiency was further facilitated in the teams that used our SW prototype (vs. physical maps), even if they worked remotely (vs. face-to-face).

*Improved Process of Sharing when Using Software*: We also found that using software in collaboration allows teams to share information more smoothly with less need for explicit coordination. We compared the percentage of "checking dialogue" acts (e.g., verifying one's own or another's understanding of previously presented information, clarifying previous information, confirming the receipt of information) between two treatments. Our analysis showed the number of checking acts in the SW teams was lower than that in the FTF teams (34% vs. 39%), and the difference is significant ($\beta = -.18(0.18)$, $p < .001$). The checking acts are one measure of the costs for coordinating a sharing process (Sanford et al., 2004). Our result shows that our software design has successfully reduced this cost.

The reduction in the need for information checking allows teams to have more time for other high-level activities, such as judging (e.g., offering individual judgment, opinion, and preference on available information). By comparing the percentage of "judging" acts between two treatments, we found that a larger proportion in the SW teams than that in the FTF teams (23% vs. 20%). The difference is significant ($\beta = -.40(0.21)$, $p < .05$).

*Good Group Performances when Using Software*: Our data showed that our software enabled the teams to perform the task with slightly faster on average compared to the teams working face-to-face on paper maps (16.63 min vs. 18.1 min). The time difference is not statistically significant ($t_{30} = 1.08$, $p = .145$). The distributed teams using our prototype also were slightly better in producing optimal plans than those meeting face-to-face with paper maps—41.7% of final plans were correct with the software treatment while 38.9% were with the face-to-face treatment. The difference is not significant using a Mann–Whitney Test ($p = .452$).

*User Feedback on User Interface*: The results from the post-test questionnaire by participants in the SW team show that the participants were satisfied with our software design. The median of the overall rating on the system was 5 in 7-point rating scale (from 1—strongly disagree to 7—strongly agree), above the neutral point (4). More specifically, participants were positive about system use (e.g., easy use of the system, easy to learn, etc.) with a median of 6, as well as user interface quality (e.g., pleasant user interface, having tools expected, etc.) with a median of 5. They were neutral about information quality (e.g., easy to find information needed, clear system message) with a median of 4.

In summary, the results from Phase I indicate that our Java-based prototype can indeed facilitate effective knowledge sharing and implicit coordination in geo-collaboration.

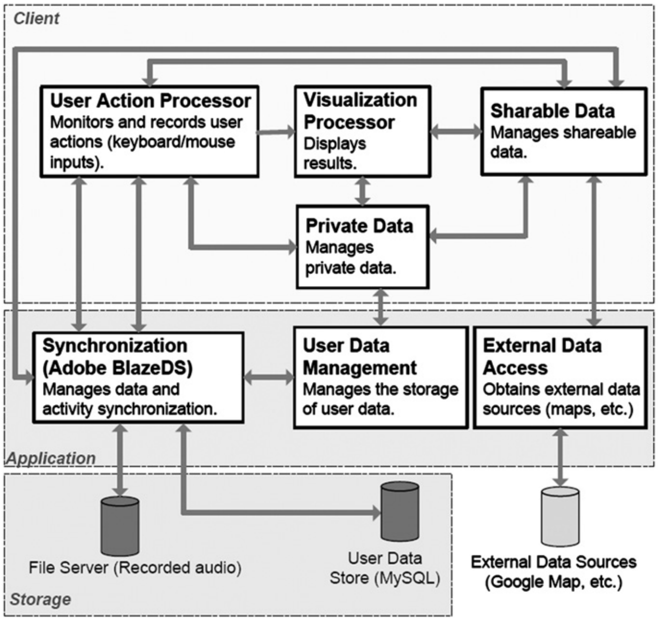


Fig. 4. System architecture of Web-based prototype.

However, both the fieldwork and lab evaluation pointed to a number of unsolved issues. Through the fieldwork, we have learned the technical constraints of installing, maintaining, and using the system. An important issue emerged from the lab study was the interaction difficulty in using the maps. As mentioned earlier, we built our maps with GeoTools, which is an open-source Java library for the organization and manipulation of geospatial data without any support for user-map interaction. We had to build all interactive tools from scratch. While we had provided a set of basic map interaction tools, such as zooming, panning, and location search, we found that participants demanded some advanced tools, such as calculating the distance between places and choosing different types of maps, to deal with some problems in analysis. Lacking such tools, participants had to shift away from their primary tasks and find other methods to address their concerns. The collaboration process and outcomes may have been affected by these limitations.

### 4.2. Phase II: Web-based prototype

The lessons learned during Phase I of this research program directed us toward a Web-based approach, which we present in this section. A set of key benefits introduced by a Web-based approach results from being able to leverage pre-existing online map services and, thus, focus on more advanced functions. Specifically, we observed three benefits. First, online map services can reduce the burden of generating, managing, and maintaining geo-spatial information. Second, online map services offer a rich set of interactive functions, obviating the need for the extra development costs of building all the functionalities from scratch, including those most basic. Furthermore, online map services can ease the burden on learning for the users, because even non-expert users nowadays are familiar with popular online map services and their functions.

Fig. 4 is the architecture of our Web-based system prototype. The architecture follows a three-tier design. The top client tier has four modules to process interactive user actions, display visual results in appropriate visualization tools, manage role-specific data not shared with others, and handle public data shared with other sense-makers. The application server tier below the client tier embeds modules to provide audio and video data, manage data storage, synchronize data across the team, and retrieve data from external sources, such as Google Maps for geo-spatial data. The storage layer at the bottom has a MySQL server to store user action and session data and a file server to store other data, such as recorded audio in collaboration.

The client is a Web-based, rich Internet application (RIA) developed with Adobe Flex. The synchronization and audio/video modules in the application server are built on Adobe BlazeDS. Other server modules are developed with Java running on a Tomcat Web server.

This RIA-based approach goes beyond http-only interactive tools (e.g., hyperlink clicking) and delivers a comprehensive graphic user interface (GUI), as seen in desktop applications, to enrich the user experience. With RIAs, we can build and maintain Web-based applications that can be deployed consistently across platforms and, more importantly, that support advanced GUI functions, such as drag and drop and free-form drawing. Currently, RIAs also can be easily integrated with server-side products to provide comprehensive collaboration and data services.

The module of external data access in the application tier serves two purposes. First, it manages the access to on-demand geo-spatial information. With this module, no maps need to be stored, managed, and maintained locally. Second, the module manages the outsourcing of certain computational tasks to appropriate services. For example, when new objects are created on maps, their geographical coordinates must be calculated. Correct latitude and longitude information is critical to the display of these objects on maps and the synchronization of these objects across the team. To avoid any potential errors, our system delegated the calculation of latitude and longitude coordinates to an external map service. In the long run, when more cloud-computing-based services are available, this module can be extended to manage other services (e.g., picture and video services that can provide images and videos associated with concerned areas). In our implementation, we chose Google Maps as our external map service, although other services such as Yahoo Maps or ArcGIS also can be used. We select the Google Maps service because its tools are more comprehensive.

Built on this architecture, the Web-based geo-collaborative system also can help to reduce overhead in deploying and maintaining the overall system. The client can be run on a Web browser, as long as the browser is equipped with the Adobe Flash player, which is free and available for different platforms. The server requires Adobe BlazeDS in a Tomcat Web server and MySQL, both of which are free and easier to install and maintain than CORK and GeoTools.

Of course, this Web-based approach also has its limitations. First, although we have embraced as many open-source products as possible (e.g., BlazeDS, Tomcat, and MySQL are either open-source or open to the general public), some tools and services do not offer transparent codes and may impose restrictions on the development, deployment, and use of Web-based applications. For example, the availability of the Google Maps service is critical to this approach, and the interruption of its service can paralyze our system. The recent outages of the Google Mail service just show the vulnerability of the dependence of online services. One way to address this issue is to integrate and rely on multiple map services, rather than just one. Second, security and privacy risks may hinder the running of complex Web-based applications. Strong security measures required to protect the data and user information on the server may increase the burdens of managing and maintaining the system. One way to deal with this challenge is to carefully classify the types of data (or layers of map data) involved and then to limit the sensitive data to local services or encrypt it if it must pass through the Internet.

#### 4.2.1. User interface of Web-based prototype

Fig. 5 shows the user interface of the Web-based system prototype. The map service integrated to this user interface is Google Maps. The overall user interface is dominated by two maps—one personal (role-specific), the other shared (team). Below the two maps is a set of tools to support collaboration and decision-making, including a chatting tool, a table to sort all annotations, a chart to aggregate annotations, and a timeline to visualize individuals' annotation activities. These tools to support decision-making are new with respect to the Java-based prototype, while the collaborative functions introduced with the earlier prototype are still supported in the Web-based prototype.

Users can interact with maps in the exactly same way as they do on the web site of Google Maps. Users can pan and zoom into and out of maps. Users can add an annotation to a location on the map by directly clicking the map (Fig. 6a), and copy an annotation from the personal map to the shared one through a clicking-initiated pop-up menu (Fig. 6b). Similarly, users can directly draw sketches on the map (Fig. 7a) and copy a sketch from the personal map to the shared one (Fig. 7b). Annotations and sketches are all color-coded according to the role of the creator, as indicated by the role color legend above the public map in Fig. 5.

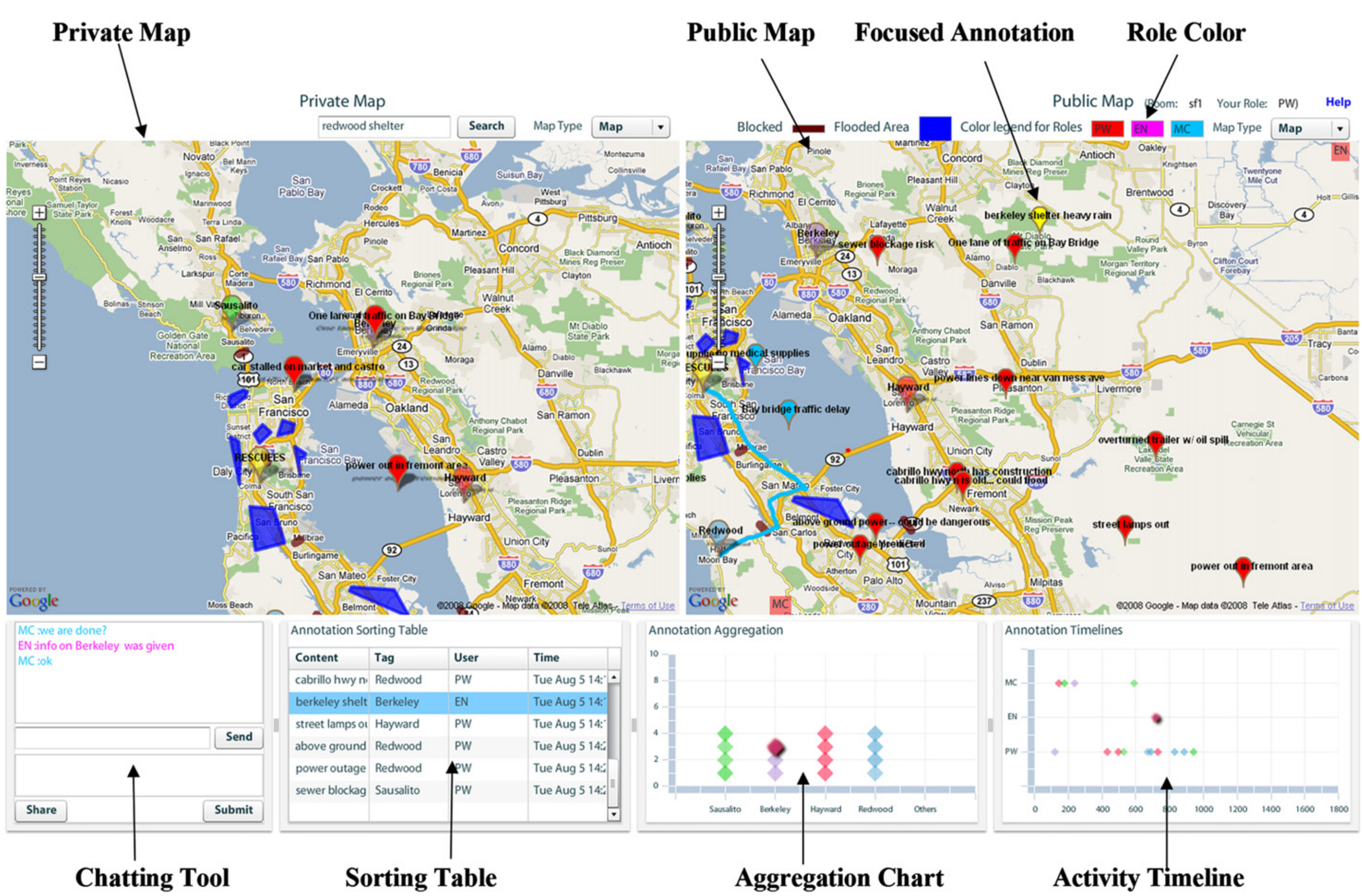


Fig. 5. User interface of Web-based prototype.

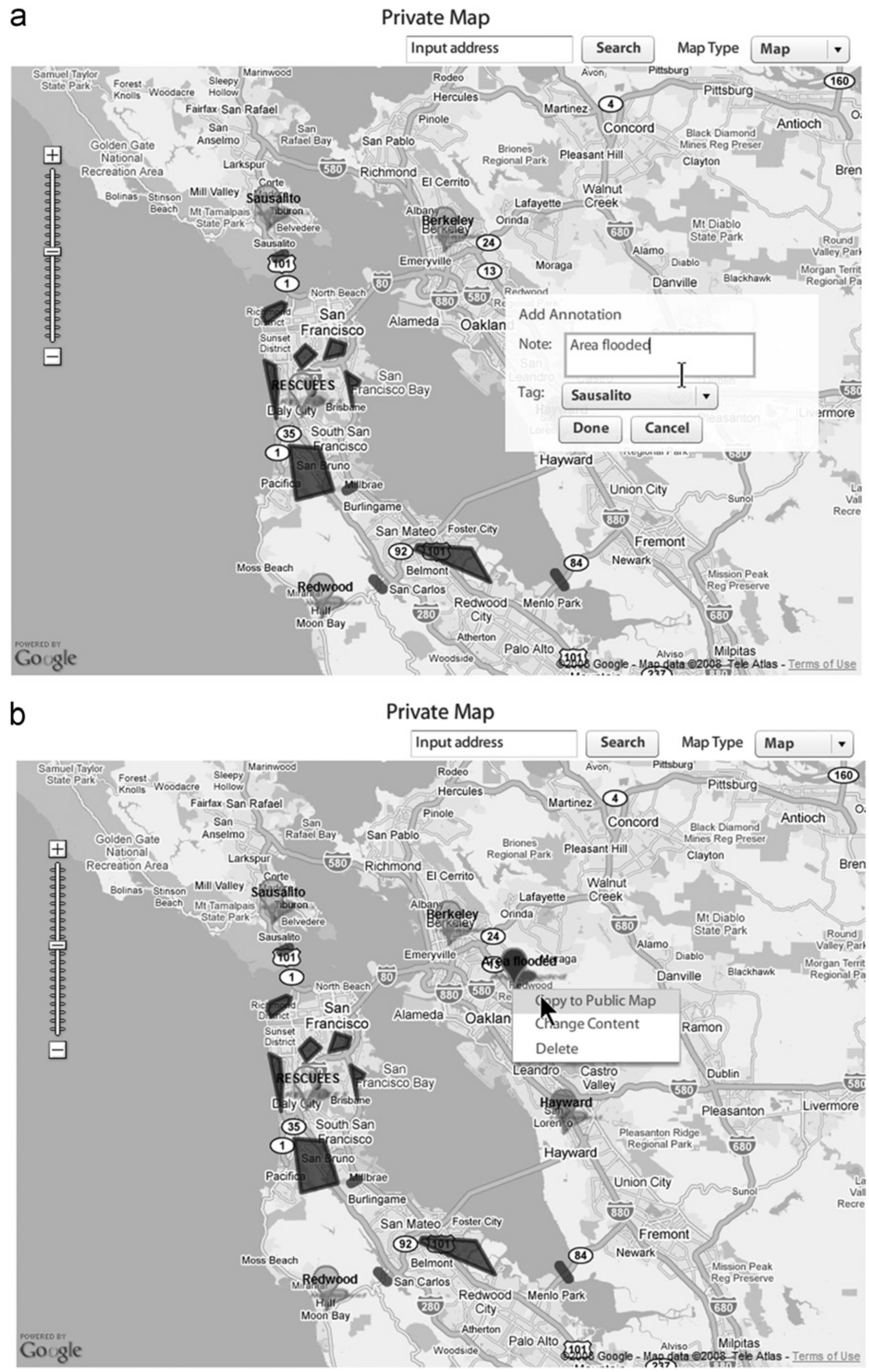


Fig. 6. Annotation activities on map. (a) Adding an annotation and (b) copying an annotation.

To help information analysis, and thus sense-making, our design also coordinates the representations of information artifacts across different tools. For example, Fig. 5 shows the view of a user who was examining the second annotation item from the table. As the item was clicked and its background turned blue, its corresponding representations in the aggregation chart (the top dot on the second column from the left) were also highlighted along with it in the timeline (the single dot in the middle line), and in the public map (the focused annotation as indicated). Seeing these different symbols of the same object in different visualization tools, the user can examine the same piece of information from different perspectives and within different contexts. Such coordinated design also helps to unite data-exploration activities and data-representation activities across maps, the sorting table, the aggregation chart, and the timeline.

### *4.2.2. Evaluation of Web-based prototype*

Again, we evaluated the Web-based prototype with fieldwork and lab study. The goal of the fieldwork was to use a focus-group interview to validate the Web-design

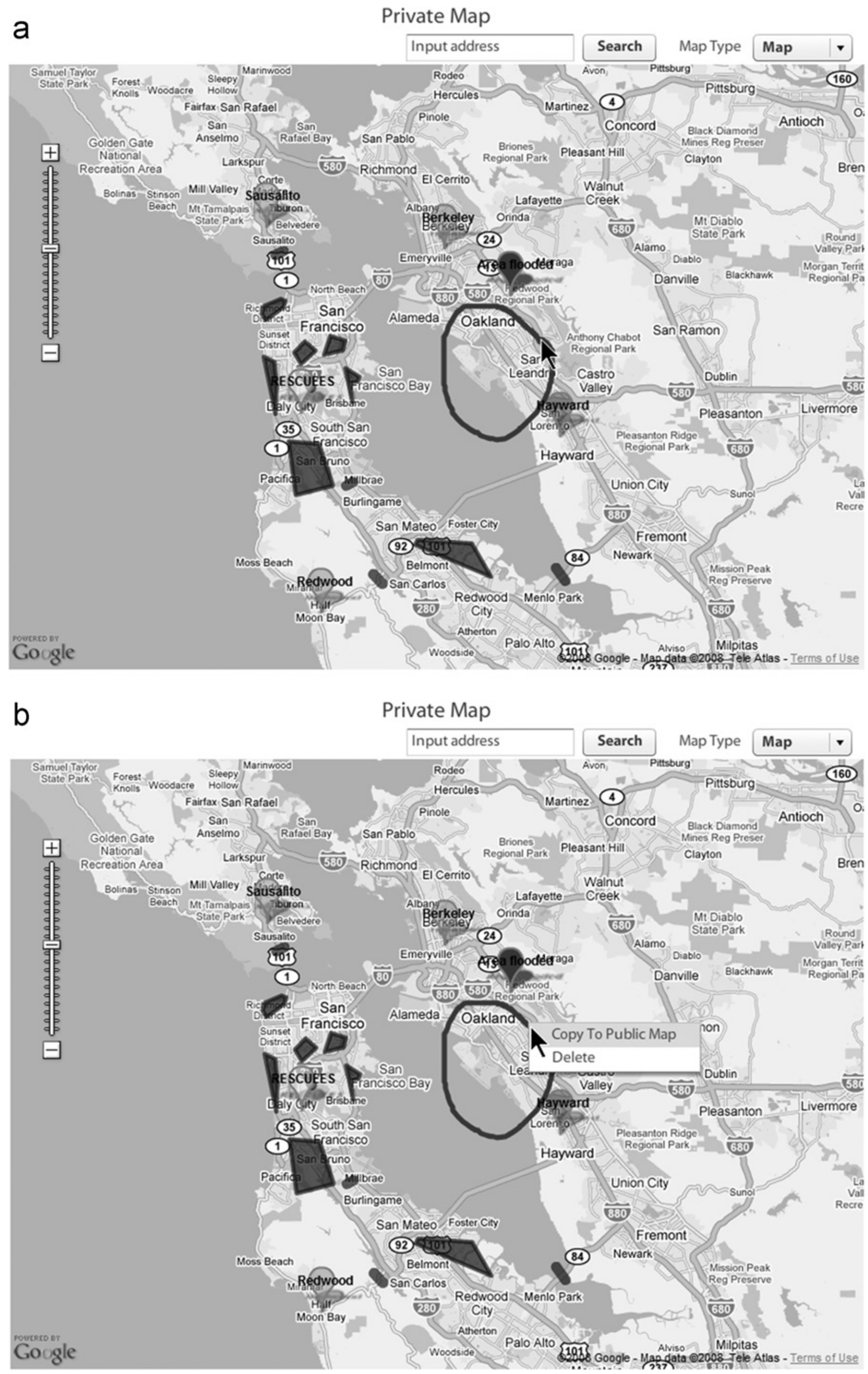


Fig. 7. Sketch activities on map. (a) Drawing a sketch and (b) copying a sketch.

approach that involves the use of online map services. The lab study had two goals: first, to compare the design of the Web-based approach with the design of the Java approach and, second, to systematically collect feedback on each component of the Web-based prototype to inform its future development.

*4.2.2.1. Fieldwork.* In the fieldwork, we presented the design to the emergency management team in central Pennsylvania and let the team leader, the emergency management coordinator (EMC), try our system. The new Web-based application impressed him. In particular, the integration of the Google Map and its map tools was regarded as a strong point because most of team members were already familiar with Google Maps. The team leader expressed a strong desire to use our system for future training and planning sessions.

We have also obtained some suggestions for further system improvement. The team wanted to see a more customizable user interface, one that would allow users to customize the presence, location, and size of various tools. Also, the team hoped that our system also could provide a new set of tools that would support cross-scale collaborative decision-making among teams from different counties, regions, and states.

One unexpected new user task was raised by the EMC when he explored our Web system. After using the tools provided our Web system, he realized that the system also would support cross-county collaboration and coordination activities in emergency management if appropriate tools could be added. Such cross-county activities had never been observed by us in table-top exercises, or mentioned by the emergency management team in any meetings. Table-top exercises were largely about within-county planning, which is centered on the tasks of local teams building action plans. In comparison, cross-county emergency management, as we learned from the EMC in this study, is more centered on the activities of sharing resource among counties through a hierarchy of authority, and also involves the state government. The two situations involve different tasks, different resources, and different geographical scopes.

The EMC and his team are responsible for emergency events in their own county as well as in neighboring counties. Inspired by our Web system, in particular the embedded online maps that allow the easy exploration of broad geographic locations and the browser-based tools that are very accessible, the EMC thought our Web system may offer good opportunities to combine both emergency tasks within the county and ones involving multiple counties.

*4.2.2.2. Lab evaluation.* In the lab study, we focused more on collecting user feedback about the design of the Web-based application, rather than analyzing group processes. This is because the Web-based application provides a set of geo-collaborative tools that is very similar to those in the Java application. First, we assessed whether or not the new prototype performed as well as the prior Java-based prototype in terms of usability (using the same participant pool and questionnaire). Second, we collected systematic feedback on the components of the prototype in order to evaluate the current design and inform future development.

*4.2.2.2.1. Participants, procedure, and apparatus.* We recruited twelve students who had participated in the study of the Java prototype for this lab study. The task and procedure in this lab study were the same as those seen in the software environment (SW) in the study of the Java prototype, except that each team only needed to complete two task scenarios rather than three. We used the same post-test questionnaire for system evaluation, the Computer System Usability test (CSU, Lewis, 1995). The usability questionnaire was extended with a set of open-ended questions, two of which pertained to the overall prototype while several other questions focused on each tool or component.

*4.2.2.2.2. Usability evaluation ratings: Overall assessment.* The average ratings (medians) of the overall Web-based prototype were positive. Similar to the evaluation results about the Java-based prototype, the medians of the ratings for the Web-based prototype were above the neutral value (4) of the scale—5 for system use quality, 5 for information quality, and 5 for interface quality.

Table 1 compares the evaluation results of the Web-based system with the results of the prior Java-based version. It is a consistent finding across the evaluations of both Java-based and Web-based systems that the participant ratings were positive about the overall design. We observed a slight increment in the ratings of quality of the interface for the Web-based tool (Median = 5 inter-quartile range = 1.2 vs. Median = 5 inter-quartile range = 3). The ratings related to system usage were slightly lower for the web-based tool than for the prior Java-based version (Median = 5 inter-quartile range = 2 vs. Median = 6 inter-quartile range = 1). This is probably due to the fact that the participants of the Web-based study were already familiar with the general idea of the system because of their participation in the prior study of the Java-based system. Thus, their experience with the Web-based system may not be as fresh as that with the Java-based system.

*4.2.2.2.3. Qualitative evaluation of the design and its components.* In addition to the quantitative usability ratings, the participants also provided open-ended feedback on the design and its components. They listed the top three positive and top three negative issues with the current design of the prototype. Then, they evaluated the usefulness and ease of use for each component: the chat tool, the personal (role-specific) map, the shared (team) map, the annotations sorting table, and the two visualizations (annotation aggregation and timeline). These questions were aimed at evaluating our design decisions. Participants could indicate what the valuable functions were, if any, and what aspects need to be improved or changed.

Table 1
Comparison of ratings between Java-based system ($N=60$) and Web-based system ($N=12$) (MED: median, IQR: inter-quartile range).

| | **Java-based** | | **Web-based** | |
|---|---|---|---|---|
| | **MED** | **IQR** | **MED** | **IQR** |
| **Overall evaluation (items 1–19)** | 5 | 2 (6–4) | 5 | 2 (6–4) |
| **System use (items 1–8)** | 6 | 1 (6–5) | 5 | 2 (6–4) |
| **Information quality (items 9–15)** | 5 | 3 (6–3) | 5 | 2 (6–4) |
| **Interface quality (items 16–18)** | 5 | 3 (6–3) | 5 | 1.2 (6–4.8) |

Not surprisingly, the chat tool and the public map were seen as the most central tools for supporting the knowledge-sharing process. The chat tool was seen as useful for discussion and clarification, comparing and analyzing, and getting a response quickly (although to some users the chat box appeared too small). The public map was seen as the main means for sharing information via the map functions of annotations or sketching; the personal (role-specific) map was seen as useful for preliminary or individual work. Regarding the maps, some users pointed to the issues of clutter, low readability, and difficult retrieval of annotations once numerous notes had been added to specific areas of the map. More advanced visualization techniques, such as text annotation clustering and aggregation, are needed to simplify the visualization and management of cluttered information.

Among the tools aimed at supporting the decision-making process (annotation table and the two visualizations), the participants considered the annotation aggregation chart as the most useful and easy to use. This tool allowed them to easily compare decision choices analyzed by the team while at the same time having an overview of all discussion results.

Subjects also raised some issues on the Web-based design. First, while the online maps offered more flexibility and freedom in information exploration and integration, subjects suggested that the current coordination mechanism among public maps be improved. Participant indicated that synchronizing the type (e.g., road map, satellite map, etc.), the location, and the scale of the public map among all team members led to competition over the control of the public map. For example, when one team member was manipulating the public map, others may interrupt his or her work. A better mechanism of public map synchronization, such as protocols on handling shared global views among multiple users (Morris et al., 2004), is needed. Second, the easiness of adding tags or text annotations led to a new need for effective tag management. Subjects indicated that with many tags, it became important to have advanced tools (e.g., data-mining tools) to group and aggregate tags so that when map is shrunk, tags will not clutter the view.

## 5. Discussion

This paper has described an iterative design research investigation of collaborative support for geo-spatial planning. Through the analysis of our two prototypes, we have made progress in mapping and managing a tradeoff space of requirements for effective geo-collaboration, specifically for operations planning tasks.

Our interest here is in augmenting collaborative sense-making by using visualization tools to externalize artifacts that are important to both individual and group activities. The system design includes multiple personal (role-specific) maps that are coordinated with a shared (team) map. Each user is presented with a personal map view and a shared map view. This reminds the users that they have a specific role to play in the collaborative activity and a specific set of responsibilities to their teammates. This multiple-view, role-based design helps them keep track of the information they have, and compare what they know with what their partners have presented in the shared map. These are significant affordances in the geo-spatial planning task that are not typical in a paper-based, face-to-face version of the task (i.e., the real world). Our evaluation indicates potential benefits of our system in support of the sense-making processes of distributed geo-collaboration.

This research also helps us develop a set of design guidelines for geo-collaboration supporting systems:

- Provide both personal (role-specific) and shared (team) maps and support information transfer between them. In collaboration, people often need personal workspace to examine information and explore options privately before sharing them with their team. People also need to share information with others through public space. In geo-collaboration, maps are what people largely focus on, so both personal and shared maps are critical.
- Provide tools that allow users to add personal comments and drawings that overlay on maps. In geo-collaboration, comments and drawings are often associated with specific geographic locations. Mapping these user-created artifacts directly onto objects on maps can improve the understanding, retrieval, and sharing of these comments and drawings.
- Provide tools for information sorting (e.g., tables) and aggregation (e.g., bar charts and timelines). In particular, when decision-making involves heavy information sense-making activities, these tools should not only allow users to manipulate and examine information in various ways, but also show the interconnections of data points from different data dimensions through coordinated views.
- Leverage online maps to reduce the burden on technology management and learning. Maps are the central artifacts in geo-collaboration, so providing maps with which people are familiar could help to reduce overhead in accessing, manipulating, and sharing geospatial information. Of course, reliance on a particular map system may face the risk of system interruption, as mentioned previously. Therefore, consideration should be given to designs that integrate multiple maps services and formats (e.g., Google Maps, Yahoo Maps). This Web-based approach offers users opportunities to collaborate from diverse devices and platforms.

We also are aware of the limitations of this research. First, our systems focus on one specific geo-collaboration task. Although the task is well grounded in empirical evidence, geo-collaboration activities can be very diverse, ranging from a small-scale evacuation due to flooding in a local community to a large-scale hurricane relief in a region. Different geo-collaboration purposes demand different tools (Cai, 2005), and our current design may have difficulty in supporting geo-collaboration activities with different natures. Second, our visualization tools are still limited. Tools like aggregation bar charts, sorting tables, and timelines may be good enough for the current task, but could be insufficient for other broader and more complicated geo-collaboration tasks. For example, people may need other advanced tools to analyze multi-dimensional data when browsing U.S. census data about a region requiring evacuation, to integrate 3-D models with maps when searching for a building in a metropolitan city, or to watch real-time photos or videos when monitoring fast-changing situations. Our current design could not help in such tasks. Furthermore, our focus here is on high-level designs concerning system architecture and visualization modules, and issues concerning tool-using behaviors, such as managing cluttered annotations and sketches on maps, have not been investigated.

## 6. Conclusion

The contribution of the work reported in this paper lies in the design research on a new collaborative system for teams doing complex geo-spatial planning tasks. Our design of a multi-view, role-based system has the potential to improve and extend collaborative tasks in emergency management. We will continue working with emergency management professionals to expand the task scope and task scenarios our system can address. Also, we will improve our design by implementing more tools so that users can choose what they need and customize the collection and layout of visualization tools in their user interface. We hope the availability of more tools and user interface customization can broaden the application scope of our system. Furthermore, we will deploy our system to emergency manage teams so that we can conduct longitudinal studies on user behaviors by collecting data on the use of the system.

## Acknowledgments

This work was funded partially by the U.S. Office of Naval research under award N000140510549 and by the National Science Foundation under Grant no. 0948601.

## Appendix. System evaluation questionnaire

**System use quality (1 strongly disagree, 4 neutral, 7 strongly agree)**

1. Overall I am satisfied with how easy it is to use this system.
2. It was simple to use this system.
3. I can effectively complete my work using this system.
4. I am able to complete my work quickly using this system.
5. I am able to efficiently complete my work using this system.
6. I feel comfortable using this system.
7. It was easy to learn to use this system.
8. I believe I became productive quickly using this system.

**Information quality (1 strongly disagree, 4 neutral, 7 strongly agree)**

9. The system gives error messages that clearly tell me how to fix problems.
10. Whenever I make a mistake using the system, I recover easily and quickly.
11. The information (such as online help, on-screen messages, and other documentation) provided with this system is clear.
12. It is easy to find the information I needed.
13. The information provided for the system is easy to understand.
14. The information is effective in helping me complete the tasks and scenarios.
15. The organization of information on the system screens is clear.

**Interface quality (1 strongly disagree, 4 neutral, 7 strongly agree)**

16. The interface of this system is pleasant.
17. I like using the interface of this system.
18. This system has all the functions and capabilities I expect it to have.

**Overall (1 strongly disagree, 4 neutral, 7 strongly agree)**

19. Overall, I am satisfied with this system.

**Open-ended questions on usefulness and usability: overall and by tool**

A. List the most negative aspects: 1...; 2...; 3...;
B. List the most positive aspects: 1...; 2...; 3...;
C. About the private map: what did you use it for?
D. About the public map: what did you use it for?
E. (*) About the chat tool: what did you use it for?
F. (*) About the annotation sorting table: was it useful and how? Was it easy to use?
G. (*) About the annotation aggregation chart (bar chart): Was it useful and how? Was it easy to use?
H. (*) About the annotation timelines chart (rightmost chart): Was it useful and how? Was it easy to use?

(*) Extra items used when evaluating the web-based prototype.

## References

Ackoff, R.L., 1989. From data to wisdom. Journal of Applied Systems Analysis 16 (1), 3–9.

Agresti, A., 2002. Categorical Data Analysis. John Wiley & Sons, NJ.

Andrienko, N., Andrienko, G., 2006. The complexity challenge to creating useful and usable geovisualization tools. In: Proceedings of GIScience 2006, 23–27, Münster, Germany.

Armstrong, M.P., Densham, P., 1995. Cartographic support for collaborative spatial decision-making. In: Proceedings of AUTOCARTO, 49–58.

Baldonado, M.Q.W., Woodruff, A., Kuchinsky, A., 2000. Guidelines for using multiple views in information visualization. In: Proceedings of the Working Conference on Advanced Visual Interfaces, 110–119.

Beenen, G., Ling, K., Wang, X., Chang, K., Frankowski, D., Resnick, P., Kraut, R.E., 2004. Using social psychology to motivate contributions to online communities. In: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work, pp. 212–221.

Bier, E.A., Card, S.K., Bodnar, J.W., 2008. Entity-based collaboration tools for intelligence analysis. In: Proceedings of the IEEE Symposium on Visual Analytics Science and Technology, pp. 99–106.

Bodnar, J.W., 2005. Making sense of massive data by hypothesis testing. Proceedings of 2005 International Conference on Intelligence Analysis. Last retrieved on March 13, 2010, from 〈http://cryptome.org/intel-2005.htm〉.

Brodlie, K., 2005. Models of collaborative visualization. In: Dykes, J., MacEachren, A., Kraak, M. (Eds.), Exploring Geovisualization. Elsevier, Amsterdam, pp. 463–475.

Brodlie, K., Fairbairn, D., Kemp, Z., Schroeder, M., 2005. Connecting people, data, resources: distributed geovisualization. In: Dykes, J., MacEachren, A., Kraak, M. (Eds.), Exploring Geovisualization. Elsevier, Amsterdam, pp. 425–444.

Cai, G., 2005. Extending distributed GIS to support geo-collaborative crisis management. Geographic Information Science 11 (1), 4.

Card, S.K., Mackinlay, J.D., Shneiderman, B., 1999. Readings in Information Visualization: Using Vision to Think. Morgan Kaufmann Publishers, Inc, San Francisco, CA, USA.

Carroll, J.M., Neale, D.C., Isenhour, P.L., Rosson, M.B., McCrickard, D.S., 2003. Notification and awareness: synchronizing task-oriented collaborative activity. International Journal of Human–Computer Studies 58 (5), 605–632.

Carroll, J.M., Rosson, M.B., Convertino, G., Ganoe, C.H., 2006. Awareness and teamwork in computer-supported collaborations. Interacting with Computers 18 (1), 21–46.

Carroll, J.M., Mentis, M., Convertino, G., Rosson, M.B., Ganoe, C., Sinha, H., Zhao, D., 2007. Prototyping collaborative geospatial emergency planning. Proceedings of ISCRAM 2007, 105–113.

Clark, H.H., Brennan, B.E., 1991. Grounding in communication. In: Resnick, L.B., Levine, J., Teasley, S.D. (Eds.), Perspectives on Socially Shared Cognition. American Psychological Association, Washington.

Clark, H.H., Krych, M.A., 2004. Speaking while monitoring addressees for understanding. Journal of Memory and Language 50 (1), 62–81.

Convertino, G., Ganoe, C., Schafer, W., Yost, B., Carroll, J.M., 2005. A multiple view approach to support common ground in distributed and synchronous geo-collaboration. In: Proceedings of the 3rd International Conference on Coordinated and Multiple Views in Exploratory Visualization, 121–132.

Convertino, G., Mentis, H.M., Rosson, M.B., Carroll, J.M., Slavkovic, A., Ganoe, C.H., 2008. Articulating common ground in cooperative work: content and process. Proceedings of the ACM Conference on Human Factors in Computing Systems 2008, 1637–1646.

Convertino, G., Billman, D., Shrager, J., Pirolli, P., Massar, J.P., 2008. The CACHE study: group effects in computer-supported collaborative analysis. Computer-Supported Cooperative Work 17 (4), 353–393.

Convertino, G., Mentis, H.M., Rosson, M., Slavkovic, A., Carroll, J.M., 2009. Supporting content and process common ground in computer-supported teamwork. Proceedings of the ACM Conference on Human Factors in Computing Systems 2009, 2339–2348.

Convertino, G., Carroll, J.M., 2011. Toward experimental methods in collaborative computing research. In: Sharlene, J., Hesse-Biber, N. (Eds.), The Handbook of Emergent Technologies in Social Research. Oxford University Press.

Convertino, G., Mentis, H.M., Slavkovic, A., Rosson, M.B., Carroll, J.M., 2011. Supporting common ground in teamwork: a design research process. in the special issue on social media and collaborative systems for crisis management. ACM Transaction of Computer–Human Interaction (TOCHI) 18 (4) Article 22.

Curry, K., 1999. Supporting collaborative awareness in tele-immersion. In: Proceedings of the IPTW '99.

DiBiase, D., 1990. Scientific visualization in the earth sciences. Bulletin of the College of Earth and Mineral Sciences 59 (2), 13–18.

DiMicco, J.M., Hollenback, K.J., Neale, D.C., Isenhour, P.L., Carroll, J.M., Rosson, M.B., 2003. The impact of increased awareness while face-to-face. Human–Computer Interaction 22, 47–96.

Dourish, P., Bellotti, V., 1992. Awareness and coordination in shared workspaces. In: Proceedings of the ACM Conference on Computer-Supported Cooperative Work 1992, 107–114.

Feibush, E., Gagvani, N., Williams, D., 2000. Visualization for situational awareness. IEEE Computer Graphics and Applications 20 (5), 38–45.

Fernandes, J.P., Fonseca, A., Pereira, L., Faria, A., Figueira, H., Henriques, I., Garção, R., Câmara, A., 1997. Visualization and interaction tools for aerial photograph mosaics. Computers & Geoscience 23 (4), 465–474.

Fuhrmann, S., Pike, W., 2005. User-centred design of collaborative geovisualization tools. In: Dykes, J., MacEachren, A., Kraak, M. (Eds.), Exploring Geovisualization. Elsevier, Amsterdam, pp. 553–576.

Gotz, D., Zhou, M., 2009. Characterizing users' visual analytic activity for insight provenance. Information Visualization 8 (1), 42–55.

Greenberg, S., Boyle, M., Laberge, J., 1999. PDAs and shared public displays: making personal information public, and public information personal. Personal Technologies 3 (1), 54–64.

Greenberg, S., Gutwin, C., Roseman, M., 1996. Semantic telepointers for groupware. Proceedings of the Australian Conference on Computer–Human interaction 1996, 54–61.

Heiser, J., Tversky, B., Silverman, M., 2004. Sketches for and from collaboration. In: Gero, J.S., Tversky, B., Knight, T. (Eds.), Visual and Spatial Reasoning in Design III. Key Centre for Design Research, Sydney, pp. 69–78.

Herring, S.C., 1993. Gender and democracy in computer-mediated communication. Electronic Journal of Communication 3, 1–17.

Isenhour, P.L., Rosson, M.B., Carroll, J.M., 2001. Supporting interactive collaboration on the Web with CORK. Interacting with Computers 13 (6), 655–676.

Jankowski, P., Nyerges, T.L., 2001. GIS for Group Decision Making. Taylor & Francis Publishers, UK.

Kemp, Z., 2005. A knowledge-based collaborative environment for geovisualization: ontologies for multiple perspectives on distributed data resources. In: Dykes, J., MacEachren, A., Kraak, M. (Eds.), Exploring Geovisualization. Elsevier, Amsterdam, pp. 295–512.

Klein, G., Moon, B., Hoffman, R.R., 2006. Making sense of sensemaking 2: a macrocognitive model. IEEE Intelligent Systems 21 (5), 88–92.

Kleinman, D.L., Serfaty, D., 1989. Team performance assessment in distributed decision making. In: Proceedings of the Interactive Networked Simulation for Training Conference, 22–27.

Kraak, M.-J., 2006. Why maps matter in GIScience. Cartographic Journal 43, 82–89.

Kraut, R.E., Gergle, D., Fussell, S.R., 2002. The use of visual information in shared visual spaces: informing the development of virtual co-presence. In: Proceedings of the ACM Conference on Computer-Supported Cooperative Work 2002, 31–40.

Lewis, J.R., 1995. IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use. International Journal of Human-Computer Interaction 7 57-57.

Lucas, P., Roth, S.F., 1996. Exploring information with Visage. Proceedings of Human Factors in Computing Systems 1996, 396–397.

MacEachren, A.M., 1995. How Maps Work: Representation, Visualization, and Design. The Guilford Press, New York.

MacEachren, A.M., Kraak, M., 2001. Research challenges in geovisualization. Cartography and Geographic Information Science 28 (1), 3–12.

MacEachren, A.M., Brewer, I., 2004. Developing a conceptual framework for visually-enabled geocollaboration. International Journal of Geographical Information Science 18 (1), 1–34.

MacEachren, A.M., 2005. Moving geovisualization toward support for group work. In: Dykes, J., MacEachren, A., Kraak, M. (Eds.), Exploring Geovisualization. Elsevier, Amsterdam, pp. 445–461.

MacEachren, A.M., Cai, G., 2006. Supporting group work in crisis management: visually mediated human-GIS-human dialogue. Environment and Planning B: Planning and Design 33 (3), 435–456.

MacMillan, J., Entin, E.E., Serfaty, D., 2004. Communication overhead: the hidden cost of team cognition. Team Cognition: Understanding the Factors that Drive Process and Performance, 61–83.

Marshall, C.C., Brush, A.J.B., 2002. From personal to shared annotations. Proceedings of the ACM Conference on Human Factors in Computing Systems 2002, 812–813.

McCarthy, J.C., Miles, V.C., Monk, A.F., 1991. An experimental study of common ground in text-based communication. Proceedings of the ACM Conference on Human Factors in Computing Systems 1991, 209–215.

Morris, M.R., Ryall, K., Shen, C., Forlines, C. Vernier, F., 2004. Beyond "social protocols": multi-user coordination policies for co-located groupware. In: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work (CSCW '04), pp. 262–265.

North, C., Shneiderman, B., 2000. Snap-together visualization: can users construct and operate coordinated visualizations? International Journal of Human–Computers Studies 53 (5), 715–739.

Olson, J.S., Olson, G.M., Storrøsten, M., Carter, M., 1992. How a group-editor changes the character of a design meeting as well as its outcome. In: Proceedings of the ACM Conference on Computer-Supported Cooperative Work 1992, 91–98.

O'Conaill, B., Whittaker, S., 1997. Characterizing, predicting, and measuring video-mediated communication: a conversational approach. In: Finn, K.E., Sellen, A.J., Wilbur, S.B. (Eds.), Video-Mediated Communication. Lawrence Erlbaum Associates, NJ, pp. 107–131.

Paul, S.A., Reddy, M., deFlitch, C.J. 2008. Collaborative sense-making: a field-study in an emergency department. Position Paper Presented at the Sense-making Workshop at the ACM Conference on Human Factors in Computing Systems, Florence, Italy. Last retrieved on March 13, 2010, from 〈http://sites.google.com/site/dmrussell2/Paul-SM-workshop-final.pdf〉.

Pirolli, P., Card, S., 2005. The sense-making process and leverage points for analyst technology as identified through cognitive task analysis. Proceedings of International Conference on Intelligence Analysis, 2–4.

Pirolli, P., Good, L., Heiser, J., Shrager, J., Hutchins, S., 2005. Evaluation of a computer support tool for analysis of competing hypotheses. Technical Report, Palo Alto Research Center. Last retrieved on March 13, 2010, from 〈http://www.cse.sc.edu/∼mgv/BNSeminar/UITR.doc〉.

Qu, Y., Furnas, G.W., 2005. Sources of structure in sense-making. Proceedings of the ACM Conference on Human Factors in Computing Systems 2005, 1989–1992.

Qu, Y., Hansen, D.L. 2008. Building shared understanding in collaborative sense-making. Position paper presented at the sense-making workshop at the ACM Conference on Human Factors in Computing Systems 2008, Florence, Italy. Last retrieved on March 13, 2010, from 〈http://sites.google.com/site/dmrussell2/Qu-SM-final.pdf〉.

Rinner, C., 2001. Argumentation maps: GIS-based discussion support for online planning. Environment and Planning B: Planning and Design 28 (6), 847–863.

Rinner, C., 2006. Argumentation mapping in collaborative spatial decision making. In: Dragicevic, S., Balram, S. (Eds.), Collaborative GIS, pp. 85–102.

Roberts, J.C., 1998. On encouraging multiple views for visualization. Proceedings of International Conference on Information Visualization 1998, 8–14.

Robinson, A., 2008. Collaborative synthesis of visual analytic results. Proceedings of IEEE Symposium on Visual Analytics Science and Technology, 67–74.

Roth, S.F., Kolojejchick, J., Mattis, J., Chuah, M.C., 1995. Sagetools: an intelligent environment for sketching, browsing, and customizing data-graphics. Proceedings of the ACM Conference on Human Factors in Computing Systems 1995, 409–410.

Russell, D.M., Stefik, M.J., Pirolli, P., Card, S.K., 1993. The cost structure of sense-making. Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems, pp. 269–276.

Sanford, A., Anderson, A.H., Mullin, J., 2004. Audio channel constraints in video-mediated communication. Interacting with Computers 16 (6), 1069–1094.

Schafer, W.A., Ganoe, C.H., Carroll, J.M., 2007. Supporting community emergency management planning through a geocollaboration software architecture. Computer Supported Cooperative Work 16 (4–5), 501–537.

Schafer, W., Carroll, J.M., Haynes, S., Abrams, S., 2008. Emergency management planning as collaborative community work. Journal of Homeland Security and Emergency Management 5 (1), 1–17.

Slater, M., Usoh, M., Steed, A., 1992. Depth of presence in virtual environments. Presence 3 (2), 130–1441994, 130–144.

Stasser, G., Titus, W., 2003. Hidden profiles: a brief history. Psychological Inquiry 3 (4), 302–311.

Thomas, J.J., Cook, K.A. (Eds.), 2005. National Visualization and Analytics Center Ch. 5, p.139.

Tversky, A., Kahneman, D., 1974. Judgment under uncertainty: heuristics and biases. Science 185 (4157), 1124–1131.

Tversky, B., 2000. Some Ways that Mmaps and Diagrams Communicate. Spatial Cognition II. Lecture Notes in Computer Science, 1849, 72–79.

Weick, K.E., Meader, D.K., 1993. Sense-making and group support systems. In: Jessup, L., Valacich, J. (Eds.), Group Support Systems: New Perspectives. Macmillan Publishing Company, New York, NY, USA, pp. 230–252.

Zhang, X., Simpson, T.W., Frecker, M., Lesieutre, G., 2010. Supporting Knowledge Exploration and Discovery in Multi-Dimensional Data with Interactive Multiscale Visualization. Journal of Engineering Design. Available Online June 23, 2010. http://dx.doi.org/10.1080/09544828.2010.487260.