Socio-Cognitive Aspects of Interoperability: Understanding Communication Task Environments among Different Organizations

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20

Emergency communication systems (ECS) are a key element in collaborations among different public safety organizations. The need for interoperability in emergency communication systems has hastened the development of interoperable communication technology that is an enabling technology to automatically identify environmental variables including appropriate radio frequencies and to connect different networks used by different organizations. Even though the technology has been researched from many perspectives and has shown that is possible to connect different organizations, there still remain many issues in terms of socio-cognitive aspects. Thus, this study examines the socio-cognitive dimensions of interoperability, which equal the technical dimensions of the problem in importance. The existential-phenomenological study reported here used semistructured interviews to reconceptualize interoperability in the public safety communication domain. Based on 11 interviews with public safety workers, five important factors were identified that have a major impact on the effectiveness of interoperable groups: information sharedness, operational awareness, communication readiness, adaptiveness, and coupledness. Based on these main concepts, high-level suggestions are provided to guide the design of a new public safety communication system. The results can be directly applied to identify the requirements of communication systems and can be extended to design collaboration systems under stressful environments.

Categories and Subject Descriptors: H.1.2 [**Models and Principles**]: User/Machine Systems—*Human factors*

General Terms: Design, Human Factors

Additional Key Words and Phrases: Socio-cognitive, interoperability, emergency communication, organization

ACM Reference Format:
Kwon, G. H., Smith-Jackson, T. L., and Bostian, C. W. 2011. Socio-cognitive aspects of interoperability: Understanding communication task environments among different organizations. ACM Trans. Comput.-Hum. Interact. 18, 4, Article 20 (December 2011), 21 pages.
DOI = 10.1145/2063231.2063234 http://doi.acm.org/10.1145/2063231.2063234

1. INTRODUCTION

Public Safety Emergency Response Service tasks must function using highly sophisticated communication systems, including computer-aided dispatch systems, handheld diagnostic tools, GPS, radios, and mobile data terminals. Recently, new interoperable

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This is a revised and expanded version of a paper that appears in the Doctoral Colloquium of ISCRAM 2010, the 7th International Conference on Information Systems for Crisis Response and Management.
This work is supported by the National Institute of Justice, Office of Justice Programs, U.S. Department of Justice, under grant 2005-IJ-CX-K017 and grant 2009-SQ-B9-K011.
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DOI 10.1145/2063231.2063234 http://doi.acm.org/10.1145/2063231.2063234

communication technologies have been introduced. However, those designing technologies to facilitate communication must still overcome major challenges due to the complexity of the work environment and organization-specific communication needs. Interoperability has become a critical concept supporting cooperation within a team or between different agencies in large operations such as unexpected simultaneous incidents, crowd control at a massive public event, or a natural disaster.

Employing new communication technologies such as software-defined radio or cognitive radio has led to considerable improvements and has ensured technical interoperability among devices on the frequencies reserved for public safety agencies [Mitola and Maguire 1999; Smith and Tolman 2000]. After the September 11 attacks, the U.S. Department of Homeland Security (DHS) raised investment to develop workable communication systems among different agencies. Even though many technical interoperability issues have been resolved by applying new technologies since then, there remains a significant number of operational interoperability issues [Department of Homeland Security 2006; Manoj and Baker 2007; Smith and Tolman 2000].

The main purpose of this study was to reconceptualize interoperability to support the socio-cognitive aspects of communications among different public safety organizations (e.g., police and emergency medical service (EMS) providers). The socio-cognitive perspective when applied to police and EMS focuses on the interdependences within social groups and the means by which these groups receive, process, and transmit information to make decisions. In particular this study was expected to: (1) gain a better understanding of the public safety domain and responses in emergency situations in terms of communication and collaboration properties, and (2) identify dimensions of the concept of socio-cognitive interoperability among agencies. To address these issues, a series of interviews were conducted with local police and Virginia Tech (VT) EMS providers. Content analysis revealed five dimensions that explained the concept of semantic interoperability. The rest of this article deals with the implications of the results of the study. By framing the concepts of interoperability in terms of the seven properties of sensemaking, we incorporate our results with existing theory. Finally we conclude that the socio-cognitive concept of interoperability leads to a series of suggestions for designing better public safety communication systems that incorporate new interoperable communication technology.

2. LITERATURE REVIEW

2.1. Emergency Response and Team Operations

Emergency situations require speedy and appropriate responses from a multiorganizational group of professionals from several different disciplines. Coordination and communication are dynamic processes among those involved, ranging from the police officers who arrive first at the scene, to the multiple organizations that then contribute, including hospital staff and volunteers. These public safety personnel must assess the incident, comprehend the situation, and project future events immediately [Endsley 1997]. When the incident is larger in scope, those processes tend to be less complete [Klein 1989; Kristensen et al. 2006]. Public safety personnel need to be able to make local decisions in the absence of a global assessment of a dynamic situation. Smaller-scale events are naturally easier to manage since their communication and tasks are limited within the organization. The larger and more critical the situation is, the more complex the collaboration. Emergency responders' work inevitably includes a combination of improvisation and standard procedures, depending on the situation [Quarantelli 1997].

A team can be defined as two or more people working together adaptively and interdependently as a unit within a large organization to reach a specific common goal [Brannick and Prince 1997]. Even though multiple factors such as availability,

Table I. Incident Command System Organization [Adapted from DHS, 2008]

Functions	Description
The Operations Section	Directs and coordinates all incident tactical operations Is typically one of the first organizations to be assigned to the incident Expands from the bottom up Has the most incident resources May have Staging Areas and/or Labor Pools and other special organizations
The Planning Section	Variables impinging primarily from sources external to the team, but may include some internal to the team (e.g. team organization)
The Logistics Section	Variables inherent to the team itself
The Finance/Administration Section	Variables impinging from sources internal and external to the team

functionality, and task objectives affect team composition, public safety incident organization is highly dependent on the precise nature of each individual emergency situation. In most cases, tasks are performed within a regular public safety organization such as a police, fire, or EMS department. When dealing with emergencies, however, the team structure and organization can change depending on the time, location, and operation. Here, the operation refers to the temporal interaction at the incident site. The goals for emergency situations may emerge unexpectedly. In a normal operation such as a routine administrative task, this type of emergent characteristic, namely a spontaneous goal, is not likely to happen. The nature of the communication within a team in an emergency situation however, differs from normal situations and is emergent, geographically distributed, and abnormal in nature [Vicente 1999]. Usually, the incident command organizational structure develops in a top-down, modular structure based on the severity and complexity of the incident, as well as the degree of danger due to the environment [Department of Homeland Security 2008].

In general, an incident organization is not correlated with the administrative structure of any single agency or organization. The individual serving as the head of a regular organization will not necessarily act as the incident commander when deployed at the emergency site. Bigley and Roberts' [2001] study described how the Incident Command System (ICS) is reliable by effective combination of three main factors: structuring mechanisms, organizational support for constrained improvisation, and cognition management methods. The ICS organization consists of four primary functional areas: operations, planning, logistics and finance, and administration. Table I shows a detailed description of each function.

The ICS organizational structure is extensible to all the elements, such as divisions, branches, and sections, depending on the type, size, scope, and complexity of a given incident [Department of Homeland Security 2008]. Whenever the need arises, the incident organization can be composed of as many as four separate sections, all of which may have their own staff. Depending on the size of the incident, an individual sometimes manages all major functional areas, or a group within the organization can be assigned to perform a specific function.

The initial response to most small incidents is typically handled by local emergency responders within a single organization. Effective emergency response requires working together at the team level within an organization or between different organizations. Although group effectiveness is hard to define, Guzzo and Dickson [1996] listed the following criteria: (a) group-produced outputs (quantity or quality, speed, customer satisfaction, and so on), (b) the consequences a group has for its members, and (c) the enhancement of a team's capacity to perform effectively in the future. Another approach is to express team performance measures in terms of outcome versus process. Although in general, teams in industrial organizations are valued largely by

their outcomes, an assessment based on outcomes is limited if there is no consideration of teamwork and work quality in the process [Brannick and Prince 1997]. As far as the public safety domain is concerned, the teamwork process is more critical in team performance measurement than the team's outcome(s) because the latter are less clear than in industrial organizations—tactical operational goals in emergency situations depend primarily on the team process. In order to function in demanding environmental conditions and perform their given tasks, teams require a wide range of knowledge, skills, and attitudes, which are called "team competencies" [Cannon-Bowers and Salas 1997]. In addition to team competencies, Paris et al. [2000] summarize a number of external and internal factors that influence team performance, namely contextual factors, structural factors, team design factors, process factors, and contingency factors, along with a set of applicable interventions.

Team composition is an important issue in a multiagency operation. In practice, even if cooperation and collaboration are indispensible to meet various task requirements in public safety work, cultural diversity in an incident organization hampers working together. The composition of a diverse group can affect the following issues in public safety work.

—Problem-solving and the decision-making process;
—The development of status hierarchies;
—Patterns of participation and communication;
—The development of cohesiveness;
—The group's ability to perform and implement decisions [Jackson 1996, p. 55].

In the context of teams consisting of multiple public safety organizations, team composition can be a very important determinant of ability to respond effectively to a large-scale disaster. For example, in a mass-disaster such as Hurricane Katrina, instantaneous team composition can be a major problem. In the case of Katrina, numerous federal, state, and local agencies had to come together to respond to rescue and recovery needs and address the material damage caused by the hurricane and its aftermath. From the earliest stages, it was clear that the leadership of the Federal Emergency Management Agency (FEMA) was incapable of organizing a multiorganizational effort in a culturally diverse environment. In particular, even though there were some specialists belonging to nongovernmental organizations involved, for example the Red Cross and the Salvation Army, working with the volunteers was very difficult because most of the volunteers were not trained when they joined the Katrina response effort and their regular organizational cultures were different from that of the emergency organizations. Diversity affected short-term cooperation at the scene as well as the long-term recovery process for the victims. Hurricane Katrina revealed a timeworn, but still controversial, problem, namely the lack of integration of the emergency services.

Sensemaking is a broad concept that can be used to explain how best to understand and project a situation characterized by high complexity or uncertainty. Sensemaking has been researched in both individual [Dervin 1983] and organizational aspects [Weick 1995]. In this research, sensemaking mainly refers to the research in organizational contexts and is defined as the ongoing effort to understand events that are usually unexpected or highly complex in organizational contexts [Klein et al. 2006a, 2006b; Weick 1995; Weick et al. 2005]. According to Weick [1995], sensemaking consists of seven interconnected properties: identity, retrospection, enacting, social, ongoing, extract cues, and plausibility over accuracy. These properties have served as a useful framework in a research area such as command and control in the military or decision-making in disaster situations.

2.2. Interoperability

From the disasters at Columbine High School and Virginia Tech, as well as natural disasters such as Hurricane Katrina, news media and official reports have called attention to the lack of interoperability among the relevant agencies. As mentioned in the introduction, interoperability is generally discussed in terms of technical issues and there have been many conferences on interoperability among the various public safety entities in recent years. The United States Congress has stated its intention to resolve the interoperability issues that have been so evident in national disasters such the 9/11 attacks [House Committee 2004].

Interoperability means different things to different people. Enterprise information systems, communication systems, and military operations all have different expectations for interoperability, for example. However, in the context of communication systems, it is closely related to technical issues that apply to specific types of hardware or systems. The Alliance for Telecommunication Industry Solutions (ATIS) defines interoperability in five different ways [Alliance for Telecommunication Industry Solutions (ATIS) 2007]:

(1) The ability of systems, units, or forces to provide services to, and accept services from, other systems, units, or forces, and to use the services so exchanged to enable them to operate together effectively;
(2) The condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users; the degree of interoperability should be defined when referring to specific cases.
(3) The state of affairs that allows applications executing on separate hardware platforms, or in multiprocessing environments on the same platform, to share data and cooperate in processing it through communications mechanisms such as remote procedure calls, transparent file access, and so on;
(4) The ability of a set of modeling and simulation processes to provide services to, and accept services from, other modeling and simulation activities, and to enable the services to operate effectively together;
(5) The capability to provide useful and cost-effective interchange of electronic data among agencies, for example, different signal formats, transmission media, applications, or performance levels.

ATIS developed these definitions for the American National Standard Institute (ANSI), who set the communication system standards for the United States and they replace ANSI T1.523, the previous version of these definitions. The International Organization for Standardization (ISO/IEC 2382-01), the Institute for Electrical and Electronics Engineering (IEEE Standard Computer Dictionary: Interoperability), and the Federal Communication Commission (FCC 1307C), have all adopted standards that are almost identical to the ANSI guidelines. In addition, many researchers paid attention to standardization and ontologies to increase the degree of information-sharing among multiple agencies in disaster response [Dwarkanath and Gusty 2010; Hernandez et al. 2010; Paulus et al. 2010; Pottebaum et al. 2010].

Beyond this technical definition, the limitations of the current concept of interoperability were identified by an ethnographic study conducted by Imran and Smith-Jackson [2005]. Thus, there is a strong need to reconceptualize interoperability in terms of the organizational and operational aspects in order to enhance the capabilities of interoperable communication systems in the public safety domain. The new approach to interoperability should therefore support information exchange procedures among

the agencies, as well as the decision-making process. Consequently, the human factors aspects of interoperability are emphasized in the next step of this study.

2.3. Summary of Literature Review

Public safety communication systems are indispensable in dealing with emergency situations. As new technologies have been introduced, communication practices and incident organizational structures have both changed to maximize the capabilities of these new technologies. Public safety communication systems both have organizational and technological constraints. This section therefore looked at general incident organizational structures and technical issues related to communication systems in the public safety domain.

As shown in Section 2.1, incident command system (ICS) organizations vary greatly depending on the types of operations. The literature reveals that there are various forms of suborganizations in the ICS organizations. A division can be created to delineate an area according to physical and location separations of terrain or other prominent features. Functional groups may then be established according to the functional needs in the operational section. If there is an incident that exceeds the span of control, the incident command system can establish a branch that is composed of a number of divisions or groups. As a primitive unit, an emergency team will be formed and managed by a higher level of authority. In general, workers in the public safety domain are highly stressed and often need to make time- and life-critical decisions. Communication is one of the most important factors governing incident organizational performance.

Interoperability has become a core concept in the public safety domain, primarily as a result of the increased number of multiple jurisdictional operations. New interoperable communication technologies have emerged within the past decade to support interoperability in various areas. While most research has focused on the technical aspects of interoperability, the need to understand semantic interoperability in the public safety domain has recently begun to be more widely appreciated and this aspect will be the focus for the research reported in the remainder of this article.

3. METHODS

3.1. Semi-Structured Interview: Existential-Phenomenological Approach

Interviews, especially semi-structured interviews, are a key technique for knowledge acquisition. The semi-structured interviews conducted for this study combined a structured agenda under three scenarios, with the flexibility to ask follow-up questions. Structured questions guide the boundaries of a topic, while open-ended questions are posed to the participant based on their responses to previous questions. Here, the interviewer sought to acquire a deep understanding of a personal experience and how each participant (first responder) explained these experiences. Researchers engaged in this type of phenomenological research generally focus on the in-depth meaning of participants' reflections and dialogues, which reveal the essence of the experience [Rossman and Rallis 2003]. Since phenomenology as a philosophy assumes that perception is highly related to the object perceived and the object of experience affects human epistemology, the interview was chosen as a good method to holistically understand the essence of public safety workers' experience in context-specific settings [Thompson et al. 1989]. This research was an exploratory study that identified appropriate measures for interoperability and refined the concepts of interoperability in terms of the properties of sensemaking. It was therefore important to understand and address the main contexts as well as the current practices in emergency communication. The narrative research explored the story of certain individuals. Each interview session lasted approximately 1.5 hours, and 15–20 questions were typically asked. Since the scenarios

Table II. Main Topics for Semi-Structured Interview

Categories	Topics
Operational Aspects	Dispatching
	Operating
	Settling
	Other emergency response procedures
	Barriers of the individual/group in the working context
Informational Aspects	Information needs in terms of the types of incident
	Presentation of information
	Input methods of information
Technological Aspects	Limitation of current technology during given tasks
	Appropriateness of technology at each communication situation
	Identification of the failure and recovery of system
	Adaptation at the specific situation with technology
	Usage pattern of the technology
Organizational Aspects	Characteristics of incident organizations
	Role allocation within the division/group/branch/organization
	Collaboration and coordination within the organization
	Structure and size of the organization

that were dealt with in the interview could be too sensitive to be recorded, at least two interviewers took notes at each interview to ensure accuracy, anonymity, and confidentiality. No one other than the researchers was aware of the identities of those who took part in the interview process. In addition, the researchers assured the participants that they could stop at any time if they began to feel uncomfortable during the interview.

3.2. Semi-Structured Interview Questionnaire

When designing the questions for an interview, two important issues should be considered [Milton 2002].

—The general research issues of self-understanding and self-change;
—The aim of developing various ways of representing people's knowledge in order to both analyse the interviews and use them in subsequent techniques.

The first issue was to elicit the participants' views on their tasks and situations, what limitations there were on each of them, and how they interacted. In the context of the public safety domain, participants' experiences with public safety events and their communication in such situations was examined. Participants' understanding and how they adapted to situations reflected their individual perspectives about current practice and the technology they used in the work domain. A descriptive approach was important to review current practices and explain how systems function in a real situation, where events do not always proceed as expected. To account for the uncertainty as events progress, this study designed the interview in such a way that it would elicit both event-based and belief-based knowledge [Milton 2002]. A pilot study was conducted to develop the interview scenarios. The preliminary interview focused on eliciting information regarding participants' understanding of how the communication system operated, which aspects of events could be reviewed during the interview, and a glossary of technical vocabulary used in the work context. This effort provided an equal or equivalent understanding of the work between the interviewee and the interviewer, as well as some level of completeness of the interview questionnaires in which the main topics were singled out for further exploration. The main topics raised in the interview, which were elecited from a result of the pilot study are shown in Table II. Although these categories were not exhaustive, they provided a good basis for the semi-structured interview questionnaire used in this study.

Another issue was the situatedness of the interview. The main claims of situated cognition are that human knowledge is not isolated from a situation or the contexts in

which it is experienced. Human perceptions, thoughts about actions, and the actions themselves are closely related to and interact with the environments in which events occur [Clancey 1997]. Since appropriate scenarios could evoke situation-specific knowledge, three different scenarios were developed based on the preliminary interview. These three different scenarios represented different working contexts, namely day-to-day, taskforce, and mutual aid situations, as specified by the Public Safety Wireless Advisory Committee [Irving 1996]. These aspects for specific operations were reviewed based on each scenario. Incorporating elicited scenarios and main topics [Table II], we developed the interview questionnaire for each scenario [Appendix A].

3.3. Recruitment

In this research, the main sampling strategy was purposeful sampling, which is defined as intentionally selecting participants who are specifically related to the event, process, or technological issues of the main topic [Patton 2002; Rossman and Rallis 2003]. In particular, the criterion sampling method was adopted here. Criterion sampling involves selecting cases "that meet some predetermined criterion of importance [Patton 2002, p. 238]." Criterion sampling is particularly beneficial for understanding information-rich cases. The main criteria of the selection were as follows.

—Participants should be familiar with public safety communication systems (at least one year working experience with portable communication systems).
—Participants should be either police officers or have some experience with police tasks; or
—Participants should be either medical emergency service providers or have some experience with the emergency medical service tasks; or
—Participants should have experience with a large-scale disaster or emergency operation (at least one year working experience at a local judicial organization or EMS). In addition;
—Sample should contain at least one participant with experience as an incident commander;
—One of the participants should have experience as an emergency dispatcher.

Based upon these criteria, regional judicial organizations, or emergency medical service providers were contacted. Both the telephone and email were utilized as the primary methods for recruiting participants.

Many researchers [Crabtree et al. 1993; Kuzel 1992] recommend that the total number of participants in studies of this type should be six to eight in order to achieve maximum variation. This study recruited 11 participants from the Virginia Tech Police Department and the VT Rescue Squad, which we believe provided sufficient variation.

3.4. Interview Procedure

The interviews were conducted between June 2007 and July 2008 with members of the VT Police Department and the VT Rescue Squad who had sufficient experience in all the different types of operations of interest: day-to-day, taskforce, and mutual-aid. Before starting the interview, the researcher briefly introduced the objectives and summarized this research and explained how confidentiality and anonymity would be ensured. The participant was then asked to read and sign the informed consent document for the interview. Once the participant had completed the form, the interviewer introduced three different scenarios and scenario-relevant questions related to (a) a football game day, (b) a fire in a large shopping mall, and (c) a case of alcohol poisoning [Appendix A].

The session began with a short introduction to a new interoperable communication system and its proposed uses. This interview focused on eliciting information regarding a critical incident where the interviewee experienced some surprise or a growing sense

of doubt with respect to how those involved in the incident had understood the situation. The interviewer asked about the participant's familiarity with the scenarios provided. In the context of the provided scenarios, the participants were asked to describe a surprise or violated expectancy and their subsequent information-seeking activity. Relative to the specific event in the scenario, they were asked how they prepared in order to recover situation awareness. Based on their responses, additional probes were used to explore the information sources, information exchange with current communication systems and face-to-face communications, and information integration would be utilized by the participant to assess the given problems. The interview continued until the technical issues related to effective sensemaking had been identified, as well as any procedural problems in communications, and the alternatives currently available for effective communications and to overcome barriers to sensemaking.

After reviewing all the scenarios, the participants were asked if they had any kind of wish list for their communication practices. The participants were asked to discuss what an ideal radio/communication device would be like, given the situation. The construct, "ideal" was described to mean a usable, effective, efficient, and satisfactory device in their work context. They were also asked to draw upon previous experiences related to informational, operational, technological, and organizational issues. All questions were open-ended and explored the participants' in-depth experience based on their prior responses.

At the end of the interview, the participants were given the opportunity to review sessions about the interview or new interoperable communication technology. All interviews were recorded by hand to ensure confidentiality. This also provided a more comfortable environment for the participants. Each interview lasted until the point of theoretical saturation was reached [Glaser and Strauss 1967; Lindlof 1995], generally after about 1.5 hours.

3.5. Content Analysis

In line with a grounded theory approach [Charmaz 1995; Glaser and Strauss 1967], two independent coders reviewed the data with no preassumptions concerning the results, as recommended by Thompson et al. [1989]. Atlas.ti (Ver. 5.5) was used to analyze the initial review; Microsoft Word 2007 and Microsoft Excel 2007 were used as additional analytic tools. The analytic procedures were based on Miles and Huberman's [1994] suggestions for encoding qualitative data. First, the coders carefully read the transcripts to obtain the overall flavor of the interviewees' responses. During the reading of the transcripts, each coder inserted codes as labels in appropriate places (Figure 1).

From these labels, each analyst developed a general category scheme of the participants' responses. For the second phase of analysis, the coders tried to identify the themes from the identified categories and subcategories. The categorization reflected the similarity of responses and frequency of responses [Myers and Oetzel 2003]. The analysts will identify themes based on the following concepts

—Themes are an expression of focus, or meaning of points.
—Theme formulations are at best a simplification.
—Themes are not objects one encounters at certain points or moments in a text.
—Themes are a form of capturing a phenomenon one is trying to understand [Van Manen 1990, p. 87].

Finally, the coders had a review session to reread the responses and identify themes to ensure goodness of fit. After all steps had been completed, the researcher determined which of the themes used to describe the concept of interoperability adequately reflected the responses provided by the participants.

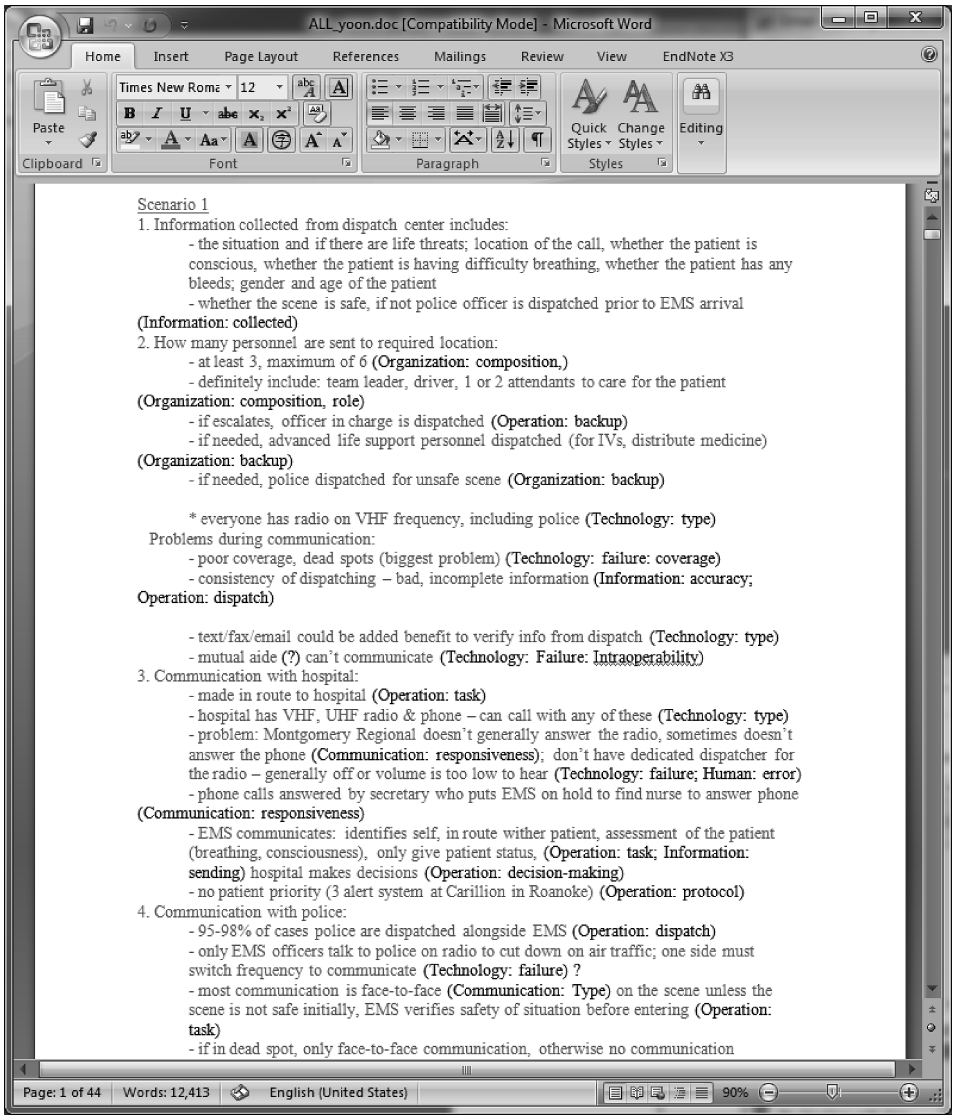

Fig. 1. Screenshot of coding.

4. RESULTS

First, in accordance with the research objectives, this study identified a set of themes that could be used to explain the concept of interoperability in the context of public safety communications. These themes were related to the collaboration and coordination required for effective team communications. Table III shows the codes and descriptions used in this analysis; note that the codes emerged from the interviews.

4.1. Information Sharedness

4.1.1. Information Asymmetry. Information asymmetry was prevalent in the interaction between the dispatcher and workers at the scene. They wanted to transfer what they knew. Most participants who were working at incidents complained that they

Table III. Identified Themes

Themes	Subthemes	Description
Information sharedness	Information asymmetry	Existing differences of information among stakeholders
	Information overload	Difficulties in decision-making caused by too much information
	Communication synchronicity	The experience of two or more communications occurring simultaneously and degree of sharing of the information at the same time
Communication Readiness	Technical readiness	Trouble with hand-held radios or other equipment due to hardware problems
	Willingness to share	Attitude to sharing collected information with other people at the same operation
Operational (group, team, network) awareness	Dynamic operational boundaries	Ability to change the operational boundaries depending on the emergency situation
	Social awareness	Knowing the person who has the right information and being aware of the existence of the right person
	Copresence	The sense of being together or awareness of the involvement of a remotely located person
Adaptiveness	Self-organization	Emerging and self-formed organization without any previous structure
	Technical adaptability	Existing alternatives or option to modify current technology to communicate with each other
Coupledness	Work coupling	Degree of functional and sequential relationship of task or work
	Distributed decision-making/Duality of centralization	Degree of centralization of decision making or relationships among decision makers

experienced insufficient information regarding the incident that they were involved in, due to a lack of communication capability. The dispatcher sometimes provided only part of the information available or the participants had not memorized all the information transferred from the dispatcher. Consistency of dispatching was important in gaining a better understanding of the situation. Human errors occurred frequently, in spite of the VT dispatchers having a list of 100 common terms to support consistency when explaining situations. Since the VT police dispatchers were not trained as emergency medical dispatchers, they had some limitations when trying to obtain accurate information (the VT police dispatch center dispatched VT Police, VTRS and the Blacksburg Fire Department). This issue was also identified in previous research that focused on interoperability in police communication [Kwon et al. 2009]. To make matters worse, sometimes the dispatchers failed to realize the importance of collecting information. Also, they did not always ask for important information since each agency had its own perspective of the same incident. Another information asymmetry existed in the communication between emergency service providers and hospitals. Perceptions and comprehension of the situation was different at each place, which led to different prognoses for the next task.

4.1.2. Information Overload. In general, individuals, including experienced police and EMS providers, under information overload cannot absorb all the required information and sometimes make vital mistakes when performing their primary tasks due to missing important information. For example, a field test for interoperability was conducted at the interoperability gateway on campus using the ACU 1000 Model at a VT home football game in 2007. The interviewees mentioned that test was unsuccessful due to excessive radio traffic and information overload. Many agents had turned off their radio systems since they were continually distracted by hearing information

irrelevant to their situation. It is not uncommon for operators to eliminate stimuli in their environment, especially when the stimuli are overloading their ability to process information.

4.1.3. Communication Synchronicity. One of the main roles of public safety communication is to synchronize and share information with other team members. In an emergency operation, they need to be able to communicate with each other at the same time and to share the same understanding of the operation, which were the characteristics of the public communication systems initially designed and developed to support real time synchronicity. However, interviewees suggested that there was a need to asynchronously refer to information. Especially in nonemergency situations such as administrative communications, they wanted to receive the information via text messages. A VT police officer mentioned that many communications were initiated to confirm past communications since their handheld communication devices did not have a function to store their communication history. Since their working situation is time-critical and very stressful, they sometimes miss information and also suffer from information overload. Another aspect of synchronicity is prioritizing information. Public safety workers received all their information through the communication systems in real time, because their communication systems were synchronized. If multiple incidents occurred simultaneously, the ability to receive only relevant information is critical to prevent information overload, as previously mentioned. Thus, in addition to considering the importance of information, the degree of synchronicity needs to be optimized.

4.2. Communication Readiness

4.2.1. Technical Readiness. The pattern of public safety communication is closely associated with the communication infrastructure and devices used. The interviewees commented that they usually carry two or more communication devices when on duty, for examples mobile phones, Nextel, and police or EMS radios. Each device is used for a specific purpose. Their official communication tool is, of course, their radio and in most cases, their communications are conducted wholly within the organization to which they belong. However, if they do need to collaborate with a different organization, the communication is usually done through a dispatch center due to the technical limitations that hamper direct communications. For example, Blacksburg EMS and Blacksburg police use different frequency bands so their communication systems are not compatible even though they frequently collaborate with each other. Consequently, they usually prepare extra radio systems to communicate with other organizations involved in an incident.

Moreover, the use of alternative communication devices is sometimes related to privacy issues. The regular communication system can be scanned by the public, so EMS personnel may sometimes use a mobile phone for sensitive medical information. There are also practical reasons to use alternative forms of communication; if there is a blind spot or a partner does not respond through the regular communication network, public safety workers usually use a personal communication device such as a cellular phone. For less formal communications, they frequently use their cellular phone for privacy, because their formal communication is automatically recorded at the dispatch station when they communicate with each other.

4.2.2. Willingness to Share. Every organization has its own culture. During the interview, police and EMS showed different attitudes toward sharing information. One police interviewee commented that sharing information was not easy since it was related to responsibility. For example, the dispatch center collects all the information provided by callers who could be the victim or a friend of the victim. They often provide

very sensitive information, raising privacy issues. As a consequence, police sometimes hesitate to share all their information with other organizations. Similarly, EMS personnel also deal with highly sensitive medical information that is very personal, and are reluctant to share it with others. On the other hand, for some emergency cases, agile sharing of information is critical since it may well be related to safety issues. As a compromise, first responders prefer to use both private and public modes to share information and maintain organizational responsibility. Thus, a permission function regarding sharing information would be necessary.

4.3. Operational (Group, Team, Network) Awareness

4.3.1. Dynamic Operational Boundaries. Operational boundaries are often flexible, based on contextual information. For example, on a football game day, when some 65,000 people gather at the same location, the public safety team is in charge of allocated sections. As usual, their operational boundary is defined by geographical constraints. However, if a large incident should occur, the operational boundary would change dynamically. In the case of multiple incidents at the same approximate location, police officers could be overloaded with the communication they are sending and receiving. Most of this information might be irrelevant or less important. In this case, it is necessary to assign different networks for each incident to avoid information-overload. In the event of an emergency case, these officers operate more than two tactical channels simultaneously. However, sharing the information provided by the tactical channels with other relevant personnel often becomes problematic. There are many usability problems involved in changing communication channels and identifying which channel a particular officer is using. Thus, if the officer has certain operational information, for example the geographical boundary, the number of people involved and the name of the appropriate channel, it may help them to be aware of their current boundary of operation.

4.3.2. Social Awareness. Unlike structured collaborations occurring in regular organizations, public safety work is intrinsically based on local and emergent organizations. Thus, it is necessary to maximize the potential advantages of being local. There is a reason for public safety personnel to be at a certain place, and this physical presence indicates more than just the fact of a person being there. In response to social awareness, the study participants suggested that knowing the identity and the expertise of the person at the scene would be very helpful when collaborating with each other. If the person can be aware of ongoing activities or can know who to contact about what, particularly at a large event, it is likely that the worker can establish a closer involvement with the event and engage in more effective interactions with the other members of the team.

4.3.3. Copresence. The era of computer mediated communication has emphasized the importance of maintaining a presence on the scene capable of gathering information quickly and accurately and then disseminating this information to where it is needed, depending on the media capacity and channels available. In public safety communications, a presence is critical because information from the scene may deal with the status of patients or life-critical incidents. The interviewees noted that there was sometimes a problem with explaining the symptoms and status of a patient to doctors. If there were some additional provision for transmitting images or videos, this could be very helpful for those involved at the scene.

4.4. Adaptiveness

4.4.1. Self-Organization. Public safety teams, especially police teams, tend to self-organize at the scene. Long-term and extensively planned operations such as football game days are performed by the formal organization. However, in some emergency

situations, their organizational structure must emerge as the incident progresses on the basis of physical and contingent constraints. For example, incident command teams may consist of volunteers, firefighters, and emergency medical service providers. It is not necessary that a decision-maker should be the highest-ranked person present at the scene; rather this will depend on the situation. Once the situation becomes more settled, the emergent organization reverts to the formal organization.

4.4.2. Technical Adaptability (Device Dependency of Communication Task). For several decades, public safety agencies have been attempting to customize their various radio systems to suit their needs, but their communication tasks have been constrained by the available technologies and systems. This problem became critical whenever a new technology was introduced, as their existing operational procedures were optimized with the then-current technology and had to be adapted to use the new equipment. The study participants hesitated to directly contact other agencies except through the dispatcher since they were not trained to do so and did not know how direct communication might disrupt organizational protocols. Not surprisingly, when the idea of new interoperable communication technology was introduced during the interview, the interviewees showed some level of concern about incompatibility with their current practices.

4.5. Coupledness

4.5.1. Work Coupling. The public safety communication boundary is highly limited by context. Normal and planned operations are performed according to the formal organization. However, in emergency situations, the organizational structure was instantaneously formed by physical and contingent constraints. Interviewees noted that although the members of VT Rescue Squad and the VT police were highly functionalized, when they were dispatched to the scene of an incident, they often changed their roles based upon the situation they found. For example, the incident commander was not necessarily a high-ranked person in the organization, but varied by situation. Thus, functional coupling becomes looser and tentative relationships may be established. Weick [1976] labeled these phenomena as a loosely coupled system, which he characterized as:

—situations where several means can produce the same result;
—a lack of coordination;
—the absence of regulations;
—highly connected networks with very slow feedback times.

Two coupling types in public safety operations often discussed, are technical couplings (between technology, task, and role) that are task-induced and authority couplings (positions, offices, rewards, sanctions) that somehow hold the organization together [Weick 1976; Orton and Weick 1990].

Once the situation is stabilized, an emergent organization turns into a formal one. In addition, operational boundaries are flexible based on contextual information. Normally, operational boundaries are defined by geographical constraints. However, if multiple incidents occur at the same location, both the operational boundaries and the degree of coupling can change as necessary.

4.5.2. Distributed Decision Making/Duality of Centralization. At the scene of an emergency, public safety workers' decision-making is critical to help save lives or prevent major disasters. Like any other police force, the VT police attempt to make quick decisions based upon the local information they already have or can obtain. They try to gather as much information as possible from all available sources. Dispatchers, people in vehicles, or people at the headquarters can collect information from the entire police database system, including data from other people in relevant places. Police organizations are

very hierarchical by nature. Thus, decision makers are usually high-ranked persons in the organization. Nevertheless, at the scene, they sometimes make locally optimized decisions in response to the situation. Due to the limitations of their current radio communication systems, the police can only transfer highly abstracted information by voice. In the scenario cases, the police officers interviewed stated they have on occasion had trouble in transferring the information that they collect and in making decisions based on incomplete information. The intrinsic characteristics of police tasks and communication capacity have rendered their decision-making distributed. In contrast, an EMS organization is highly functionalized, which means their decisions are distributed to people in situ. In addition to communication capacity, there are many barriers to effective collaboration, including environmental issues such as blind spots or noise, organizational issues such as individual and organizational cultures, and privacy issues.

5. THEORETICAL UNDERSTANDING OF INTEROPERABILITY

In the results section, this study reviewed the dimensions of interoperability based on the results of the qualitative study. This section reviews the dimensions of interoperability from the point of view of organizational sensemaking. Recently, Alberts and Hayes [2003] discussed the four domains of warfare: physical, information, cognitive, and social domains. In this perspective, the concept of interoperability should incorporate these four levels of domain. Interoperability has a major role in the battlefield, enabling troops to share information and maintain situational awareness. Making information more available to all participants is in fact, the main purpose for introducing the concept of interoperability. However, this notion has been extended as a concept to support coordination and cooperation in intra- and inter-organizational operations. In such contexts, both concepts of interoperability and sensemaking have become crucial to support military organizational performance [Alberts and Hayes 2003]. In addition, Weick et al. [2005] have said, "The image of sensemaking as activity that talks events and organizations into existence suggests that patterns of organizing are located in the actions and conversations that occur on behalf of the presumed organization and in the texts of those activities that are preserved in social structures" [Weick et al. 2005, p. 413]. This treats communication as a core component of sensemaking and organizing. Thus, the concept of sensemaking provides a good theoretical framework to reconceptualize socio-cognitive interoperability in the public safety domain and its communication system. The following seven properties would also be applicable in the public safety domain.

—*Grounded in identity construction.* Making sense of the environment influences everything, including one's self-understanding. For example, how public safety workers define their own mission and capabilities depends on their personal identity and includes aspects such as the organization they belong to and their role in the organization. This shapes how they interpret events and is strongly related to operational awareness as well as coupledness. The identity would be established through long-term involvement in the organization and emergency operations and could be the basis of their cultural perspectives towards public safety operations.

—*Retrospective.* Making sense of the present event is always grounded in past experience. Past decisions affect current decisions to adopt certain strategies and objectives. For example, how public safety workers make sense of an emergency situation will be shaped by their experience. A police officer familiar with drug investigations is likely to collect the evidence related to drugs at a homicide scene and make decisions based on that past experience.

Enactive of sensible environment. Making sense involves the construction of reality by interactively assigning attention to the context of an event. For example, instead

of attempting to get as much information about an emergency situation as possible, a commander may focus only on those aspects of the emergency situation that interactively fit certain patterns of thinking derived from his or her past experience. New interoperable communication technology may facilitate their interactions with the operational environment and provide sensible information to the commanders.

—*Social.* Making sense relies on what other people related to tasks are thinking and doing. In this case, it emphasizes creating shared meanings and experiences that guide commanders in their organizational decision-making. This is one of the most important concepts of sensemaking and is related to most dimensions of interoperability. For example, a public safety incident organization involves many decision makers at various levels, all of whom affect each other's decision making. They need to share their respective goals and vision for the situation. Coupledness explains the degree of coupling among decision makers. This is also related to the type of operational awareness that identifies the boundaries of operation as well as social awareness.

—*Ongoing.* Making sense is a continuous process that causes individuals to perceive, comprehend, take action, and repair a given situation. For example, a public safety worker's tasks are likely to involve understanding, goal-directed planning, sharing information, and executing it in a dynamic environment. Information sharedness refers to the ongoing activity of sharing information to make decisions at the scene.

—*Focused on and by extracted cues.* Sensemaking is based on cues that are extracted and noticed from the environment. The people involved in the situation contextually interpret those cues according to certain experiences, mental models, and patterns. For example, particularly when facing time stress and situational ambiguity, experts in the public safety domain will intuitively focus on key events and patterns they can see, and make decisions to develop the course of the operation.

—*Driven by plausibility rather than accuracy.* Sensemaking seeks to find feasible or optimal solutions rather than the correct solution. For example, when faced with a situation of uncertainty or information overload, public safety workers try to understand their cues at an executable level, thus helping them to make a timely decision in order to maintain momentum and gain an advantage over uncertainty.

6. IMPLICATIONS

Highly distributed decision-making processes are problematic for situations involving multiple communication channels. Decision-making, in this context, is geographically and organizationally distributed. It can be made by people at the scene, dispatch centers, vehicles, and other control centers at different levels of organization. In every decision-making task, the communication group shares situational knowledge. Consequently, this study characterized the concept of interoperability as a unit of decision-making in terms of the joint cognitive systems involved [Cannon-Bowers and Salas 2001; Hollnagel and Woods 2005; Hutchins 1995]. Each unit needs to have sufficient capacity to collect and transfer the information in order to yield a seamless decision-making process. A new interoperable communication system needs to be able to support the transfer of multimodal data, including texts, images, or videos. In addition, device usability is important when the situation becomes increasingly complex.

Direct communication with appropriate personnel can address many of the time-critical issues in emergency communication. However, this should be done in parallel with appropriate contextual information, such as the people who are part of the current communication network, information related to the incident commander, and the physical and contextual boundaries of the current operation. Appropriately prioritizing networks and displaying channel information may be a solution that will enhance the efficiency and effectiveness of emergency communications.

In interoperable work systems, information asymmetry is an inevitable problem. Decision-making in this emergency context is geographically and organizationally distributed, which is one of the main reasons for distributed decision-making. At present, synchronous communication is the default mode, but asynchronous communication may help users to retain information and make it easier to compare past information with current information in real time. The expansion of communication capacity in terms of multimodality should also help to reduce information asymmetry.

Information overload remains a serious problem. Emergency responders require access to pertinent information and simultaneous isolation from irrelevant information. Thus, it is important to support dynamic team composition at the interface and system levels. Understanding the communication patterns of public safety workers and organizational issues in context-specific settings may be a way to solve the problem of information overload.

The context of an incident can determine the best configuration for the interoperable communication group, which may be a decision-group, incident command organizational group, or a geographical-operational group, as appropriate. Based on the parameters of operational boundaries, it is possible to prioritize communication networks that support interoperable groups with interoperable communication devices. This type of divided communication facilitates building more valid and relevant decision-making process models that are compatible with joint cognitive systems. In this context, a communication system should identify current operational boundaries. The police, for instance, use three or four communication networks for a single operation. In general, communication networks support the communication within an organization. Yet, even though the police have dedicated tactical channels, they are not often utilized. The people directing the operation need to know who is involved in this particular operation and how to contact them. To support this need, the communication system should present the boundaries of operation geographically as well as organizationally.

When it comes to introducing new technology, designers tend to start their design from analyses of current practices, with new practices being created based on current devices. This iterative and inductive logic eventually prevents innovative design in new communication systems.

Finally, interoperability can be described in terms of self-organization characteristics, which emerge from operations, and is highly distributed, and nonspecific [Vicente 1999]. It is essential to present the organizational information clearly in communication devices in order to support effective communication. For example, people in the operation need to be able to identify the person who is in charge of the case. This may be critical, especially, in the case of multigroup operations. The functional unit also needs to be represented in their communication system to support direct communication between stakeholders [Vicente 1999].

7. CONCLUSION

7.1. Overall Outcomes and Contribution

In spite of the huge amount of research that has been devoted to the technical aspects of interoperability in public safety situations [Dilmaghani and Rao 2006; National Task Force on Interoperability (NTFI) 2003; Smith and Tolman 2000], this complex system requirement remains an unsolved problem. As yet, there is no effective approach that supports interoperability in the context of public safety. The complexity of interoperability lies in the multiple and dynamic layers for socio-cognitive demands. Five themes were identified that explain the socio-cognitive aspects of interoperability and could potentially be applied to improve public safety communication task performance. These themes and the result of the interviews were delineated according to the

seven properties of sensemaking. This was an important process designed to identify precisely how interoperability affects organizational decision-making and performance and explaining this by means of the concept of sensemaking. This descriptive approach was adopted in order to provide an in-depth understanding of public safety communication tasks and apply the results to design improved technical systems as well as social organizations that can make best use of the new systems. Descriptive efforts help to advance future efforts to conceptualize, model, quantify, and structure socio-cognitive dimensions of interoperability and communication systems in public safety, with particular applications to emergency and disaster situations. These descriptions, from the perspectives of public safety personnel, also revealed how stressful it is to implement many communication tasks and how limited the existing systems are in terms of supporting effective and efficient communication. It is hoped that this better socio-cognitive understanding of interoperability will contribute to research into how the current communication technology influences user behaviors in the context of loosely coupled systems.

The methods and results of this study can also be used in other similar areas such as military communication systems or complex socio-technical systems requiring timely decisions and close coordination. Understanding interoperability in terms of the properties of sensemaking has provided a sound theoretical basis from which the concept of interoperability will serve as a core concept for resolving complex communication tasks. Weick et al. [2005] emphasized how important communication is in the organizational decision-making process. As this study showed, the concept of interoperability is essentially a property of inter- and intra-organizational communication. Consequently, this may be an important variable explaining how such organizational sensemaking can be achieved. Considered alongside Klein's macrocognitive model [Klein et al. 2006a] as an understanding of sensemaking, the concept of interoperability can be used as a mechanism to explain the macroperspective of the group decision-making process.

In sum, interoperability has been the subject of a great deal of debate during the past decade due to its importance in communication systems. However, to date there has been little systematic research to identify the semantic concepts of interoperability in the public safety domain. This research has identified the concepts governing interoperability using a systematic approach and suggested a model of interoperability. Based on the model of interoperability presented here, interoperable communication systems were modeled and reviewed. The results of this research are applicable to similar application domains, including military communication systems, as well as complex control systems.

7.2. Limitations and Future Study

Despite all the methodological care taken in this study, several factors should be understood regarding its limits of applicability. This phenomenological study was based on an in-depth understanding of the experience of the participants. Thus, the results of the study depended on those individuals who participated in this research; their level of experience was an important aspect of this study, as well as the time they had spent in their posts and the positions they held. To ensure a minimum level of experience and some variety in the positions held by the participants, criterion sampling was used as a type of purposeful sampling. Even though the researchers tried to contact a wide range of the available public safety organizations in the United States, all of the participants in this study belonged to the Virginia Tech Police Department and Rescue Squad. So, it is possible that there were some unknown patterns of behavior peculiar to this geographical area and these organizations, which skewed the responses. To minimize the bias and maximize the variability, the participants' various experiences in public safety

operations were confirmed. In addition, the small sample size limited the ability of our results to provide deeper and broader insights.

Multiple coders were employed for this study. However, we did not measure intercoder reliability. We assumed intercoder reliability could be very high because the abstraction process had already occurred when the interviewers noted the contents of the interview. The coder analyzed the condensed contents by the note-taker. As previously stated, a pilot study was conducted to collect a set of three scenarios that reflected the breadth of their communication tasks in the context of day-to-day, task force, and mutual aid, respectively [Irving 1996]. Although scenarios were provided, the results may include superficial answers to the phenomena related to the synthetic experience. Because the nature of public safety work is frequently critical, many security and legal issues had to be addressed and restricted our ability to use scenarios that were associated with highly uncertain events such as shootings. For example, the participants often hesitated to describe sensitive issues during the interviews even though the confidentiality of the contents of the interview, survey, and focus group was repeatedly emphasized. Finally, there may have been a subjective bias during the analysis. To avoid this, the study used an interpretative group based on the recommendations by Thompson et al. [1989].

As this study has shown, communication among different organizations under stressful environments is a critical function in public safety operations. First and foremost, this study provides a theoretical background to assist in the design of complex collaboration systems under stressful environments. The result of the study can directly convert to design guidelines or constraints for safety critical systems. In addition, the findings can serve as the theoretical basis to develop an instrument to measure socio-cognitive interoperability. When we can quantitatively measure the degree of socio-cognitive interoperability, the output can be design parameters of public safety communication systems. Second, this research has shown that applying the interoperable communication concept will enhance current communication practices by facilitating the implementation of joint cognitive communication systems. Current communication systems only focus on the core communication capability for one agency. We can obtain more context-oriented design requirements to support multiple agencies by incorporating the concept of socio-cognitive interoperability into the early design phase.

ELECTRONIC APPENDIX

The electronic appendix for this article can be accessed in the ACM Digital Library.

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Received March 2011; revised July 2011; accepted August 2011