

An Activity Theory Analysis of Search & Rescue Collective Sensemaking and Planning Practices

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ABSTRACT

Search and rescue (SAR), a disaster response activity performed to locate and save victims, primarily involves collective sensemaking and planning. SAR responders learn to search and navigate the environment, process information about buildings, and collaboratively plan with maps. We synthesize data from five sources, including field observations and interviews, to understand the informational components of SAR and how information is recorded and communicated. We apply activity theory, uncovering unforeseen factors that are relevant to the design of collaboration systems and training solutions. Through our analysis, we derive design implications to support collaborative information technology and training systems: mixing physical and digital mapping; mixing individual and collective mapping; building for different levels and sources of information; and building for different rules, roles, and activities.

CCS CONCEPTS

• **Human-centered computing** → *Field studies*; **Ethnographic studies**; **Empirical studies in collaborative and social computing**; • **Applied computing** → *Cartography*.

KEYWORDS

search and rescue, training, practice, sensemaking, planning, maps, activity theory.

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1 INTRODUCTION

Search and rescue (SAR¹) is a multi-hazard discipline needed for a variety of disasters [134]. Members of a SAR team assemble specific activities – *operations*: locating persons in distress or imminent danger; providing medical assistance, food, and shelter to survivors; and providing ground-zero updates to the public and other responders [41, 52–54, 56]. There are different types of SAR operations (e.g., urban search and rescue² (USAR³, US&R), mountain rescue⁴).

Cooperative work, planning, and spatio-temporal skills are crucial to success in this complex socio-technical activity [122, 130]. Much of this team-based work is unpredictable in nature, so team members (referred to as SAR responders or just responders from this point forward) constantly train. Students engaged in SAR training must learn to search and navigate the environment, make sense of unpredictable situations, and collaboratively plan operations. However, traditional training methods, such as real-life simulated drills and classroom courses, present challenges in advancing SAR training [8]. Training in classroom environments lacks realism while real-life drills may be unavailable, costly, and risky [8, 83, 130]. New approaches to SAR training are needed.

If classroom environments offer little realism and real-life drills are too burdensome, we suggest a hybrid of the two. SAR training

¹Our participants pronounce “SAR” as a word, not spelled out, so we treat it as such in text.

²<https://www.fema.gov/urban-search-rescue>

³Our participants pronounce this like “you-sar”.

⁴Mountain Rescue Association: <http://mra.org>

stands to benefit greatly from advances in mobile and wearable technologies [55, 56, 82, 83]. Information technology support in disaster spaces is currently spreading quickly. However, there are open questions on how best to support situated practice in enabling coordination in disaster spaces [122, 131]. We expect these hybrid training spaces to support research in HCI, specifically mixed and augmented reality systems.

SAR work practice presently involves little information technology, yet SAR is unique space of inquiry for both system design and training support. Its uniqueness and potential is due to SAR being comprised of multiple interconnected activities, artifacts, and regulations each lending themselves to a rich context for innovation. Prior research around this space has focused on incident command and has seen little uptake [43, 56, 84, 122, 130, 131], yet near-future mobile technology now holds promise to impact field operations [8, 106].

The present research characterizes information use in SAR to understand practitioner use of, interest in, and concerns about technology. Prior work by HCI and CSCW researchers in crisis response, organizational sensemaking, and disaster training have provided a deep understanding of the complexities of this socio-technical workspace. For example, studies of disaster response practice contributed rich insight, providing new ways to improve training and field operations through system design (e.g., [44, 56, 89, 122, 131]).

Each of these studies investigates different components of disaster response: collaboration and coordination practices [76, 130, 131], sensemaking in emergencies [98], situational uncertainty of disaster response [56], and on-line social convergence in disaster [70]. While this work is expansive, sensemaking and planning in SAR is critical to successful operations but has not yet been explored in-depth. How SAR responders come to internalize their training to plan and make sense while in the field is a much needed space of inquiry. Based on our study of prior work (e.g., [7, 56, 76, 122, 131]) and motivation to develop new means to enable SAR training and coordination, the research question driving our study is: **What are**

the informational components of SAR practice and how is information recorded and communicated?

By addressing our research question, we contribute an in-depth account of SAR collective sensemaking and planning practices present in SAR praxis embedded in their training exercises. This is assembled through an examination of inter-connected themes across five data sources: (1) taking online SAR courses (January 2018), (2) SAR training facility visits (January 2018), (3) in-person interviews with SAR professionals (January 2018), (4) an online questionnaire of SAR professionals (January–July 2018), and (5) analyzing documents and artifacts from SAR operations (January–July 2018). Table 1 provides a summary of these data sources and additional detail.

To synthesize the themes of each data source, we draw on *activity theory* (AT), a conceptual framework organized around the fundamental concept of purposeful work *activity* [80, 101]. AT was used to provide an analytical framework for to study and help unpack the interconnected components relevant to collective sensemaking and planning practices, similar to prior studies [7, 13, 36, 96, 118, 136]. In the present research, the activity being analyzed is search and rescue (SAR).

We contribute design implications for building interfaces that support SAR in the field, as well as implications for how training should be carried out after incorporating that technology. The implications highlight what aspects of the SAR activity can be technologically augmented: mixing physical and digital mapping; mixing individual and collective mapping; building for different levels and sources of information; and building for different rules, roles, and activities. These implications should guide building new SAR training simulations (e.g., mixed reality games [8, 97, 130]) and collaborative information interfaces.

SAR is a socio-technical system that bridges physical, digital, and geographic spaces. As a socio-technical system, SAR is unique for HCI spaces in that it is not only currently “low-tech” but tech-avoiding due to technology’s fragility. By bringing SAR to HCI, we provide a rich area for research and design focusing on practical

Table 1: All triangulated data sources, with number of each (No.), and details.

Data Source	No.	Details
Online Training Courses	2	The primary researcher completed two SAR online training courses, which are designed for SAR personnel. The two courses were: the <i>Technical Search Specialist Training</i> and the <i>Planning Team Training</i> offered by the Texas A&M Engineering Extension Service (TEEX). Both courses were completed before visiting the SAR facilities and conducting the interviews.
SAR Facility Visits	2	To gain insights into SAR practices and training, we visited a well-known SAR training facility, Disaster City (College Station, Texas, USA) and the Texas Task Force 1 headquarters (College Station, Texas, USA). Observations, documents and artifacts were recorded and collected during the visits.
Interviews	3	Face-to-face semi-structured interviews with professional SAR responders and instructors. The length of each interview lasted between 90 to 120 minutes. Interviews and questionnaires are included as supplementary materials.
Questionnaires	4	To reach skilled SAR professionals, an online questionnaire was sent to high-ranked SAR responders.
Documents & Artifacts	12	Documents and artifacts were collected from online resources of SAR teams across the southwestern region of the USA.

deployment that concurrently increases the resiliency of information communication technology. The present research extends prior work in disaster response practice and training and encourage future research in this area.

2 THEORETICAL BACKGROUND: ACTIVITY THEORY

HCI and CSCW have a long history of using theoretical frameworks to study context to influence future design needs [66, 79, 123]. Theoretical frameworks, such as distributed cognition [6, 69, 131], actor-network-theory [90, 91, 117], and AT [13, 33, 36] have been deployed to give contexts more hybridity, use more depth, and users more freedom.

Kaptelinin and Nardi argue that when people interact with technology, “*the doing of the activity in a rich social matrix of people and artifacts*” [80, p9] helps ground the analysis of such interaction. AT is a conceptual framework that helps to understand “*specific uses of specific technologies*” [102, p202]. AT is organized around the fundamental concept of *activity*, which is defined as the: “*purposeful interaction of any subject with the world where mutual transformation between subject-object are accomplished*” [80, p71].

AT differs from other post-cognitive theories in that it treats *activity* as the main unit of analysis and rejects the concept that people and artifacts (e.g., computers) are equivalent [80]. Activity is treated as a collective-conscious goal-directed process undertaken by multiple people to accomplish a shared objective [80]. AT develops a triangular model: a three-way interaction between subjects, objects (i.e., objectives), and community, which are mediated by tools, rules, and division of labor (e.g., Figure 3). AT has been used in prior research to analyze cultures and work practices (e.g., healthcare [13], education [36], autonomous aircraft operations [45], disaster response [19, 33]) and is proven to be a robust lens to examine work and practice [15, 49, 80, 101].

2.0.1 Activity Theory in Analyzing Disaster Response. AT has been used as a lens in prior studies of disaster response work [7, 19, 33, 96, 118, 136]. Valecha et al. [136] conducted an activity theory analysis of emergency dispatch incident reports. The authors analyzed more than 1,000 emergency dispatch incident reports to develop a conceptual modeling grammar, as a unifying language and tool, to help responders share their expertise. AT helped the authors to extract “*key concepts embedded in task-critical information supplied by the emergency communities of responders*”. In our work, we include incident reports as a *tool* that mediate information sharing and collaboration activities within the SAR activity system.

Shankar et al. [118] studied the 2008 Mumbai terror attacks through an activity theory analysis and identified lessons learned and discussed the key dimensions of effective emergency response. AT helped the authors by identifying the “*mechanism for evaluation of the crisis and the development of security policies, standards and practice*”. Policies and standards are seen in our current work as *rules* that govern how emergency response is performed, which can not be separated from the whole activity system.

MacMillan et al. [96] echoed the insights of both prior studies and proposed AT as a methodological and analytical framework in studying information practices in emergency management. The authors only investigated officers with tactical command, or *Silver*

Commanders, in the UK and through an activity theory analysis, they showed how such complex activity can be unpacked using AT. The authors argue that AT can provide “*a holistic approach to understanding the work activities context unlike some other analytical methodologies, as it focuses on use of artifacts for the interaction of humans with their environment*” [96, p.1].

As a complex socio-technical activity, SAR is ideal for decomposition through AT similar to these prior studies. However, in our current work we bringing SAR to HCI by contributing an in-depth account of SAR collective sensemaking and planning practices and training. We expect that this work extend prior work in disaster response and encourage future research in this area.

2.0.2 Role of Activity Theory in HCI. AT has been applied as a framework in numerous HCI and CSCW research (e.g., [7, 13, 19, 33, 36, 45, 96, 118, 136]). When searching for articles about AT within HCI, we find a large number of search hits produced by using (“activity theory”: 2,119 hits) and (“activity theory” + “HCI”: 993 hits) as search strings in the ACM Digital Library⁵. The number of search hits implies that numerous studies are employing or discussing AT within the field of HCI, which has been valued as a theoretical framework for HCI [79, 80]. Kaptelinin and Nardi argue that the contribution of AT to the field of HCI can be divided into three types: “(a) theoretical re-framing of some of the most basic HCI concepts, (b) providing conceptual tools for design and evaluation, and (c) serving as a theoretical lens in empirical studie” [79, p5].

A full literature review of the role of AT in the field of HCI is beyond the scope of this paper, but we point readers to existing surveys on the topic [27, 79, 80, 101, 143]. In this work, we use AT as a theoretical lens to understand SAR collective sensemaking and planning practices and training.

3 CONTEXTUAL BACKGROUND: DISASTER RESPONSE & TEAM COORDINATION

In this section establish a number of terms and concepts that relate to the practice of disaster response and how teams coordinate in disaster response contexts. We expect these concepts to enable to reader to better understand the context of this research and the concepts that arise in discussing it.

3.1 Sensemaking & Planning

Sensemaking is a process of collecting data for situation awareness to make decisions [3, 141, 142]. Prior research has studied the importance and methods of sensemaking in multiple contexts, e.g., command and control [3–5, 71], collaborative information seeking [107, 108], education [114], organizational science [142], and team training [67].

Situation awareness is the ability to understand the state of the environment and predict future states [46–48]. This type of awareness is critical in distributed teams where team members must inform one another of personal status, situation status, and actions [3, 65, 131, 145]. A number of artifacts aid situation awareness, reducing potential contradictions. These technologies are the artifacts of SAR and form an essential component of sensemaking and planning necessary for SAR activity.

⁵<https://dl.acm.org>. Search performed on January 10, 2021.

Prior studies characterize *information seeking* as an essential component of sensemaking [129, 142]. Information seeking involves collecting, filtering, processing, authenticating, and interpreting information in order to extract what is needed for situation awareness [3, 5]. The use of artifacts like information visualization techniques (e.g., interactive maps) supports sensemaking [56, 120], allowing teammates to share information, synchronize their activities, and maintain awareness [64].

Sensemaking is often social [142]; involving people with different backgrounds. The outcome of sensemaking is affected by members' team skills [22, 71]. Team members need to have the knowledge and skills to work with each other to contribute productively [22]. Sensemaking processes are used to produce *plans*: a series of anticipated actions designed to achieve an objective [127]. Planning activities are undertaken by individuals and teams to make decisions and synchronize effort, and form a fundamental component of disaster response [130, 134]. During any planning process, information is gathered and analyzed from different sources to establish a strategy that will lead to accomplishing a goal. *Collaborative planning* is undertaken by teams to develop a set of actions that can lead to solving a problem or achieving a shared goal [130]. Shared mental models and collective sensemaking are important for the success of collaborative planning [130].

However, Suchman [126] argues that plans should be considered as representations of future actions, an "*imaginative reflection*", that in itself stands outside of actions and are not moments of situated actions. *Situated actions* implies that actions depends on the specific circumstances during which the action is intended to be performed [95, 126, 127]. This concept suggests that we should not represent plans as predefined rational courses of actions without taking into consideration how subjects use their circumstances to perform these actions [95].

3.2 Disaster Response & Incident Command

Disaster response consists of a complex set of interconnected activities to mitigate the effect of an *incident*: "*An occurrence... that requires a response to protect life or property.*" [134, p140]. Incident command (IC) is a set of activities that involve developing and executing plans in response to disasters and is the primary way that response is organized. The perspective of the present research is in the context of the United States, although similar structures exist in other countries. The United States National Incident Management System (NIMS) [53, 134], governs how IC structures form and disband for incidents of varying scale. For small incidents (e.g., a missing hiker), a lone *incident commander* makes all high-level decisions and provides direction. The same system specifies more complex hierarchies to manage large-scale incidents (e.g., Hurricane Harvey), which may have either a single incident commander or a group, called *unified command*, at top and federated branches to handle aspects of response (e.g., operations, planning). As the need for response declines, NIMS specifies how the structure reduces in complexity [130].

The Federal Emergency Management Agency (FEMA), an agency of the United States Department of Homeland Security (DHS), establishes policy and leads the coordination of the National Urban Search and Rescue System. SAR *Task Forces* are trained and

equipped by FEMA to handle the nation's SAR needs. Each SAR Task Force is associated with a state and given a number (e.g., Texas Task Force 1). These teams are capable of mustering and deploying to any part of the country within four hours, being fully self-sufficient for at least 72 hours. Incident Support Teams support the SAR Task Forces by providing qualified specialists to manage and support deployed system task forces [51].

4 PRIOR STUDIES OF DISASTER RESPONSE & SAR

Prior research has used qualitative methods to deeply understand the nature of disaster response and improve training and operations through system design (e.g., [43, 56, 84, 122, 130, 131]). Many of these studies rely on fieldwork, in which a researcher is immersed in the life of the people they study to uncover practice [1]. Prior studies have looked at humanitarian assistance during disaster response [98], situational uncertainty of response efforts [56], and on-line social convergence during disaster [70, 88], resulting in rich data about disaster response work practice.

Toups et al. [130–132] developed a deep understanding of the reality of firefighting and disaster response work, which informed the design of training simulations. The research team conducted a number of different observations of disaster response practices: interviews with professional emergency responders and observations of students performing burn training exercises, urban SAR full-scale exercises, and IC simulations. Through these field observations, the researchers contribute a set of design principles in the form of implications for system design and game design patterns [21, 42, 130] that enable designers to develop training games and simulations that engage players in disaster-response-style planning [9, 10, 58, 87].

Prior studies have also investigated geographic information systems and crisis mapping used in disaster response work and training [6, 43, 55, 56, 122]. Fischer et al. [55, 56] studied disaster response work through designing a bird's-eye-view mapping system for disaster response planning. This research guided the design of systems that help augment and enrich disaster response. Other systems provide support for tabletop map-based planning and sensemaking and are relevant to our study, they are designed for co-located permanent or temporary control rooms [55, 56, 86, 111].

Teleoperated and semi-autonomous robots (i.e., drones) are currently being integrated into SAR teams [58]. These robots are capable of searching for victims, identifying dangerous areas, collecting environmental and sensory data and mapping locations. Murphy et al. [26, 28, 100] investigated rescue robots extensively and showed how they can be used in the aftermath of disasters such as the World Trade Center disaster and Hurricanes Katrina. However, current approaches to human-robot teamwork training can be challenging due to the lack of cost-efficient available training [8, 58]. New approaches to SAR training are needed.

Through several studies with SAR responders, Jones et al. [74, 76–78] contributed an extensive understanding of distributed collaboration within SAR teams in Canada. Through a qualitative study of SAR remote communication practices, the authors showed that different communication modalities and information streams (e.g.,

voice, text, photos) has its own advantages and disadvantages. Having multiple modalities of communication can help improve distributed collaboration. The authors work helped inform the design of remote-collaboration technologies, such as tangible interfaces, for supporting SAR collaborative work and team awareness [77]. Similarly, Chenji et al. [34] designed DistressNet, a system that help SAR responders reduce the time needed to respond to an incident by collecting and presenting environmental and sensory data and mapping locations in one tool. The authors focused on finding ways to improve SAR response time within different activities such as victim detection, information collection, and detection of lost responders. We build on these studies and extend it by providing an in-depth account of current SAR collective sensemaking and planning practices and training and provide implications to support the design of new and innovative collaborative information technology and training systems.

An extensive number of research efforts investigated the use of microblogging data in disasters (e.g., [11, 29, 40, 60, 106, 113, 124, 125, 137, 144]). Wong-Villacres et al. [144] investigated how social media have supported informal crisis response during the 2016 earthquake in Ecuador. The authors showed that such platforms fell short in providing effective humanitarian logistics in crisis response and provided recommendations for technology design to improve the use of such data. All of these prior studies together show that the quality and reliability of such microblogging data need to be measured carefully in order to be used by responders. We extend prior work by examining how current SAR responders use microblogging data within their sensemaking and planning activities and how they measure the quality and reliability of such data.

A full literature review of prior disaster response work is beyond the scope of this paper, but we point readers to Palen et al.'s living bibliography on crisis informatics [105]. In the current study, we focus on the activity of SAR.

5 DATA COLLECTION: SOURCES & METHODS

We begin this section by highlighting the researchers' background to help readers understand where and why this research began and where it is going. Like many researchers in HCI, the authors of this paper work and live among different realms of scholarship. Collectively, our work centers around disaster response practice and training and crisis informatics. Through years of qualitative observations, the researchers developed a deep understanding of different aspects of disaster response work, which has informed the design of training simulations that engage participants in disaster-response-style practice.

We develop a deeper understanding of SAR sensemaking and planning with the purpose of building new systems for operations and training. The present research builds on five complementary data collection methods and sources that address our research question; Table 1 offers an overview.

Online Training Courses: To gain first-person experience with SAR training, the primary researcher began by completing two online training courses designed for SAR personnel offered by the Texas A&M Engineering Extension Service (TEEX⁶). This activity

primed the researcher, developing understanding of the activities and vocabulary used by SAR responders, as well as established common ground by taking courses those responders took previously. These online courses are a prerequisite to any SAR field training: (1) *Technical Search Specialist Training* (16 hours): search and structure-marking standards, navigating (e.g., compass, map, GPS), and using visual and listening search equipment; and (2) *Planning Team Training* (8 hours): planning processes, situation reporting and documentation, GPS use in the environment, and search operation data collection and reporting.

During the courses, observations and screenshots of training materials were recorded, focusing on how sensemaking and planning activities take place within the socio-technical aspects of SAR. The researcher then used these insights and learning outcomes from these courses to discuss them during the SAR visits and with the participants and the rest of the research team to critically reflect on how such practice and training is conducted and can be design for.

SAR Facility Visits: Next, we visited a SAR training facility (Disaster City in College Station, Texas, USA) and a SAR operations headquarter (Texas Task Force 1 headquarters in College Station, Texas, USA) in order to gain insights into SAR practices and training (Figures 1 and 2). These visits involved touring the training ground; talking with SAR members; taking observation notes; and photographing artifacts (e.g., maps, forms, training materials) used in practice and training. All collected documents and artifacts were discussed with SAR professionals, when possible, to understand their use, provenance, and how they mediate SAR.

Interviews: While on site, we conducted in-depth face-to-face interviews with SAR responders to understand planning practices and training methods. The interviews engaged responders in an open discussion about their experiences. The interview protocol involved a series of open-ended questions and follow-up questions focusing on responders' experience, technical background, factors affecting the success of a SAR planning, and future vision for SAR work and training. All responders we interviewed had been deployed to the 2017 hurricanes Harvey and Maria, which provided a grounded and current view of how SAR work is performed. Each interview lasted 90–120 minutes, each participant was provided an information letter and signed a consent form. Questions for the interviews are included in supplementary material. The interviews were audio recorded and later transcribed and analyzed.

Online Questionnaire: Recruiting experienced disaster responders and SAR leaders is challenging [8, 106]. Such experts are difficult to reach; their time is valuable. To reach additional participants, we sent an online questionnaire to SAR responders. The questionnaire included all the main interview questions; participants were asked to elaborate as much as possible in their responses. The online questionnaire allowed us to reach out to highly experienced and SAR leaders with impressive experience (Table 2). The questionnaire instrument is included as supplementary material.

Online Documents & Artifacts: We identified key documentation from online resources of different SAR teams across the southwest of the USA. We explored each SAR team's website to identify key documents used for training and strategy, artifacts used by these teams, and information that could provide valuable insight. We considered this task exploratory, and did not apply a systematic method to collect materials.

⁶<https://teex.org>



Figure 1: Photos taken during a visit to Disaster City training facility in College Station, Texas, USA. A. A collapsed structure prop used for training on different complex forms of search and rescue techniques such as shoring, breaching, bracing, and use of dog, and B. a train wreck prop is used for real-life drills and training on specialized SAR techniques, such as rescue in confined spaces. Using these props, responders can train on SAR techniques, such as conducting different physical search methods, using listening and visual devices, breaching concrete, and canine search training. (Photos taken by Z O. Toups).

5.1 Data Collection Method Rationale and Challenges Encountered

These five complementary data sources were necessary to provide a deep understanding of SAR work. Much SAR practice is developed at a local level, so we strove for depth with sources close to us, but also worked outside of the contacts with which we had developed rapport. These data sources complement each other and provided a multifaceted view of SAR, providing more diverse input and triangulating findings. For example, interviewees discussed how paper maps are critical to use and train for in SAR, which was also observed during the facility visits and how large amount of paper maps are used to make sense of disasters and plan strategy. We even noted the availability of printers in command posts used to produce new paper maps. Within the training courses, we were able to see first hand how maps can be learned and how SAR training is conducted for this specific skill. Online documents from other SAR organizations helped us to understand how SAR teams learn such skills, regardless of a specific team.

While we reached out to several SAR training facilities and responders in the USA to conduct visits, interviews, and surveys, only these facilities and participants agreed to participate. Such

recruitment challenges within disaster response and crisis informatics research have been highlighted previously [8, 106, 113]. The number of SAR participants in this study is limited; however, we argue that we extend understanding of SAR practice by triangulating different data sources, methods, and level of experience. By augmenting interviews with surveys and evaluation of artifacts, we are able to adequately answer our research question and contribute insight that interviews alone would not bring out [59, 94]. This variety of expertise (Table 2) provides a diverse view of SAR practice and training relevant to sensemaking and planning.

6 DATA ANALYSIS

For the present research, we collected qualitative data aimed at building an understanding of practice. We first undertook thematic analysis, developed open coding and emerging themes were identified. It later became apparent that AT was a useful means to frame the collected data and we used it as a lens. We see this theory as a means through which to contextualize how SAR team members come to internalize many of the routines currently deployed in SAR. The result of the AT analysis (Figure 3) provides direct insights into our research question.

Table 2: Participant details, separated by interviewees and questionnaire respondents: identifier (ID), age, SAR position(s) held, and years of experience (Exp.).

Interviewees				Questionnaire Respondents			
ID	Age	SAR Position(s)	Exp.	ID	Age	SAR Position(s)	Exp.
P1	59	Task Force instructor	32	P4	58	Task Force & rescue squad leader	30
P2	34	Task Force training manager	10	P5	64	Planning chief	35
P3	35	Task Force technician	12	P6	61	Search team leader	28
				P7	36	SAR volunteer	8

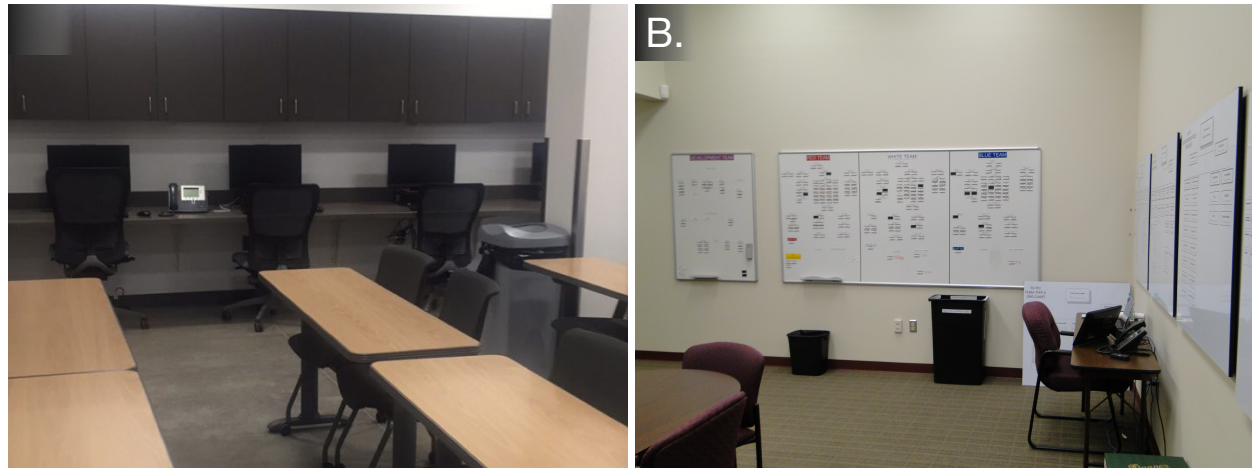


Figure 2: Photos taken during a visit to Texas Task Force 1 headquarters in College Station, Texas, USA. A. Classrooms are used by responders for meetings and to undertake in-class, online, and computer-mediated training. B. Planning rooms are used for exercise and scenario development, in which whiteboards and printed large paper maps can be examined and studied to help in sensemaking and planning practice and training. (Photos taken ☺♻️ Sultan A. Alharthi).

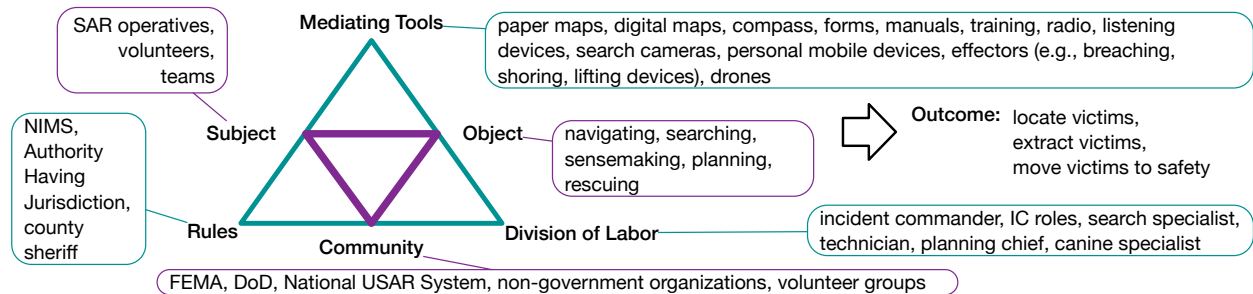


Figure 3: The developed AT framework, incorporating all discovered components of performing SAR. This represents a high-level view of the activity.

6.1 Unifying Data Sources through Thematic Analysis

Thematic analysis is a set of techniques that summarize and develop insights about the characteristics of a data corpus [24]. The process consists of a series of iterative coding cycles, performed individually and collectively by researchers, with an interest in finding commonalities within a data corpus to develop insights. The stages of thematic analysis are iterative and repeat.

First, all data were grouped for easy access and coding. As each of the coders engaged the data, we began to identify potential themes around the concepts of information seeking, sensemaking, and planning. For example, some of the data discussed moving between physical and digital artifacts, marking locations on a map, and jurisdictional procedures. As the data were coded, they were additionally grouped by theme. When all of the data was coded, we then began to code our data more in-depth.

We examined the themes the data were assigned and created sub-categories or new themes as they emerged. One aspect of these categories and themes that emerged was that the data lent itself to AT. As a result, we connected all of our themes, categories, and coding to AT. Connecting these data to AT allowed us to identify the central activities of SAR and answer our research question. This was followed with multiple discussion sessions to discuss how each researcher agreed or disagreed with the codes assigned to the data. While refining and constructing new categories and relationships, a final review of the data was conducted to contextualize the final themes and situate the findings.

6.2 Activity Theory Analysis

In this work, we draw on AT [49, 80] to frame SAR practice and training. AT was selected as a theoretical lens in this work for two reasons. First, the activity system itself is a useful unit of analysis that can identify the main components of SAR, which helped us unpack the interconnected components relevant to collective

sensemaking and planning practices. Second, AT helped us to understand and characterize the interactions, tensions, and contradictions within the complex socio-technical environment of SAR, which can help drive future system design.

We worked from the results of our thematic analysis, particularly in phase 3, above, and returned to our unified data corpus to re-evaluate the data as needed.

An AT description is one way of knowing that supports our research question. We first identify the *activity* to analyze; in this case, a SAR operation, from which we provide the following insights:

- (1) better understanding of the activities undertaken by SAR professionals in practice;
- (2) identifying how information is collected and made sense of individually and collectively by responders;
- (3) identifying the uses of both technical and non-technical tools (e.g., paper, digital form);
- (4) understanding how these tools mediate activities;
- (5) identifying how plans are constructed, shared, tracked; and
- (6) understanding how training is structured and performed.

We connected emerging themes observed in the data to the core elements of AT: *Subjects, Objects, Community, Mediating Tools, Rules, and Division of Labor* as we coded [80] (Figure 3). Such connections helped to identify the central activity of SAR. Our iterative process developed a set of questions, based on AT [80]: who are the subjects?, what are the objects of the activity?, what tools are used?, how do these tools mediate the activity?, what are the main contradictions and tensions?, and how do each of these components influence SAR activity? This resulted in an analysis focusing on the individual and collective interaction between responders and artifacts used in SAR work and training. In the following, we discuss the main activity analysis and describe the connections between the core elements of AT and SAR practice (Figure 3).

AT's value is in disassembling an activity, rendering its components and relationships accessible [15, 16, 49, 50, 80, 101]. As we disassembled SAR as an activity, thematic analysis allowed us to contextualize community, rules, tools, divisions of labor, and moments of contradiction. The result is that AT with thematic analysis allows us to break down the interconnected components of SAR practice to discuss how they are being used. Additionally, we are able to see what tensions and contradictions exist between the different components of the SAR activity system, and how these influence SAR practice.

AT is often used to evaluate concurrent activities [13]. Bardram & Doryab conducted two cases of activity analysis inside a hospital. The authors show that clinicians were handling as many as 14 concurrent activities during a day shift, in which they frequently switch between them [13]. In their work, the authors show how activity analysis can provide detailed insights into the activity of an individual actor, as well as collaborative and concurrent activities in teams.

Within SAR, there are numerous individual, collaborative, and concurrent activities being performed at any given time. The *central activity* analyzed in this work is *performing SAR*. There are multiple *subjects*, including individual SAR operatives, volunteers, and teams. Each of these subjects is a type of responder; even with small incidents, this represents a large number of people.

A responder is part of a variety of potentially overlapping *communities* (e.g., National USAR System, FEMA, US Department of Defense). Each individual might simultaneously operate as more than one community (e.g., a member of a state task force might become a FEMA operative if federal aid is activated). Each community influences how responders understand the makeup of a SAR operation. Within SAR operations, an individual responder is locally oriented as a member of a team of two to six people. These small teams work closely to accomplish a set of *objects*.

We identify a number of actions in SAR to achieve these outcomes. The desired *outcomes* of SAR include locating victims, extracting them, and moving them to safety. In order to accomplish these outcomes, SAR responders must use objectives such as: navigate the outdoors, make sense of the situation, provide actionable intelligence to the SAR and other supporting teams, and plan for further action.

Many *tools* mediate the activity of SAR, including compasses, paper maps, digital maps, radio, forms, technical tools, listening devices, drones, etc. Responders at ground zero will communicate with a base of operations and one another through radio and reify their work and understanding of the area through shared maps. Tool use depends on the nature of the response area: e.g., radio serves when cellular access is unavailable; paper maps when digital are not viable.

The team's work is governed by the formal *division of labor*, which often resembles responders marking critical locations on the map. Those marks lead to responders then maintaining constant awareness of the area. Responder actions change based on the information from other supporting personnel and the *rules* that govern how SAR is performed (e.g., if local authority having jurisdiction (AHJ) does not want to spray paint buildings when marking them, responders must use stickers).

The AT analysis revealed rich cultural and contextual factors that influence SAR work and training. One concept that we did not discuss in this initial analysis are those tensions and contradictions that the SAR team members need adjust for. AT did allow us to identify the main tensions commonly found within SAR work, which point to how training can influence activity systems. Through understanding these tensions and contradictions, AT next shows us how training can be designed to simulate essential components of SAR practice and how training courses can be conducted to improve practice.

7 FINDINGS

In this section, we synthesize our findings from the thematic and AT analyses (Figure 3). We connect our understanding of key SAR activities and practice through quotes from interviews and survey data. We then discuss design implications based on these themes. Table 2 is used for source attribution.

Our analysis identifies the primary SAR activities of *sensemaking* and *planning*, which are mediated through tools (e.g., maps, forms, radio) and activities that are undertaken by individuals and teams to make decisions. These activities are governed by rules of NIMS [134] and the local AHJ [12], which guide the hierarchy of responsibility among responders and contribute to how labor is divided. SAR activities include collecting information, assessing

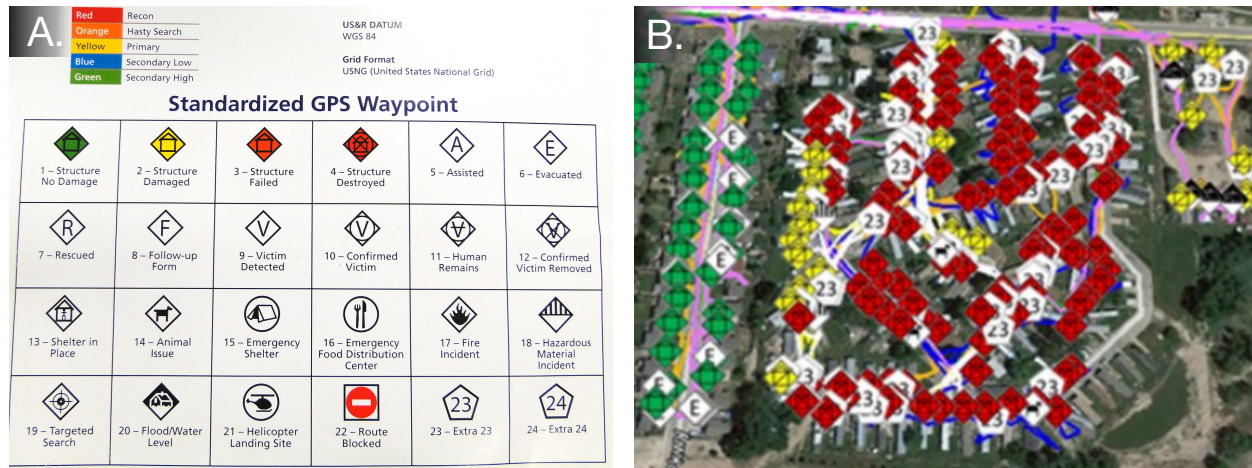


Figure 4: A. Standardized GPS waypoints chart used in digital maps. B. A digital map annotated with these standard GPS waypoint markers during SAR operations. (Photos taken © Sultan A. Alharthi).

damage and needs to determine the scope and magnitude of the incident; marking key locations on maps; and constructing plans for SAR [12].

Both training and practice are central to disaster response work and they both strongly rely on each other [8, 131]. When SAR responders learn a new skill, such as using a compass, they engage in different training activities to gain the knowledge and skill needed. Practice, however, is applying what they learned over and over to gain or maintain proficiency in it. Our findings provide valuable insights into both the training and practice aspects of SAR work.

7.1 Sensemaking through Reconnaissance

During any SAR mission, information is gathered and analyzed from multiple sources to make sense of an incident and establish a plan [40]. Individual and collective *sensemaking* and *information seeking* are essential:

when the initial event occurs, I would say TV and radio, and social media... and internet are the primary means of learning about what it is that have happened... it might be several hours, before we get the call that we are going, we are already collecting these information. [P1]

The information-seeking activities performed by responders can be divided into two phases: initial overall data collection about the incident; and systematic information collection of reliable and actionable intelligence from “boots on the ground” and official sources [130].

While information disseminated through news outlets and social media (e.g., geospatial data, photos, videos) [137], helps responders and the public develop an initial understanding of the situation [120], responders treat such information with caution:

it is almost not information, because we do not want to consider it as intelligence, but it is more of data that we collect, analyze, and build it into something,

because what you see in TV might not look as bad as it is or it might be far worse than that... but we collect all that almost immediately, and get a sense of how big it is and how bad it is, how real it is, and what is the potential impact to the citizens of the area. [P1]

While not all responders are called to action, they still engage in collective sensemaking to ensure readiness. These initial processes are part of how responders develop situation awareness of an incident and are a source of potential contradiction and tension in development of the response activity.

When responders are called into action, information is gathered in a well-established, systematic process. Such processes are done through *reconnaissance*, the preliminary survey of the affected area and/or assigned area of operation for the purpose of making sense of an incident, determining its scope and magnitude, and identifying needed resources [12, 128].

Processes of Reconnaissance: Processes of reconnaissance aim at determining how best to locate and rescue victims, as well as analyze the safety of an area. *Structure triage assessment* involves identifying which buildings most likely contain victims and assessing stability, which is used to determine what shoring the building might need and how safe it is to search. Responders perform structure triage assessment, physically mark buildings with triage information, and record structures on a map:

along the way clues, hazards, or other items may be discovered and the coordinates of those locations need to be collected and transmitted to others. [12, p.104].

This activity helps to make sense of the incident and identify, select, and prioritize the places with the highest probability of success with respect to finding and rescuing live victims. Such information is shared with responders and the Command Post through different artifacts.

Artifacts of Reconnaissance: Artifacts influence how information is retrieved, filtered, shared, and made sense of:

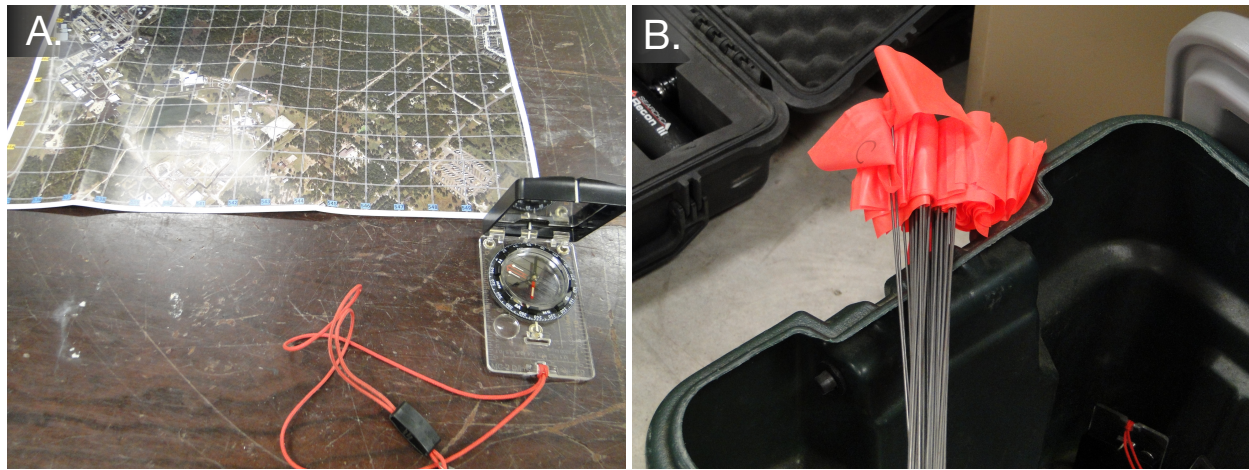


Figure 5: Basic tools used by SAR responders for outdoor navigation and information seeking. A. Compass and paper maps used for navigation and orientation, and B. Stake flags to place as a trail in the Hansel and Gretel survival strategy. All photos taken during a visit to a SAR training facility (Disaster City, College Station, Texas, USA). (Photos taken © Sultan A. Alharthi).

most relevant information is sent back via radio or voice communication, send back by email, or send back using the common operating platform [mapping and GIS systems] that we use [P2].

While this information is shared through radio and other voice and text-based communication tools, we observed that geospatial tools were primary [11, 81, 110, 121]. Due to the nature of SAR activities, geospatial data are connected to relevant information about the incident [73, 109]. Through such processes, responders develop an intelligence picture, allowing them to work together and plan operations:

the common operating picture platform we use, provide a lot more information faster. Instead of having to wait for the GPS to come back [from the different reconnaissance missions and from each individual responder], it shares the information from mobile devices, tablets, and phones, and we are getting that feedback nearly instantaneously as well as pictures, and more than just a symbology, but also, text about what occurred, when, where, who, and any relevant information into real intelligence, actionable intelligence [P2]

One important outcome from the initial reconnaissance activity is the creation of, operational zones.

Operational Zones, Tensions, & Contradictions within Recon: Operational zones, are formed as a result of division of labor, subjects, and tools, ensuring the safety of responders and the public [99]. The *cold zone* is a safe area and includes all the personnel and equipment that are not actively involved in the SAR operation; it includes the Command Post, media, and public. The *warm zone* is the staging area between the hot zone and the cold zone; it contains personnel and equipment essential to the support of SAR. The *hot zone* is the incident area in which SAR takes place. Only equipped

personnel are allowed in this area. The sizes of these zones depend on the conditions specific to each incident [99].

We observed differences in information representation needs among operational zones. Tensions arise from these differences that influence how responders collaborate. For example, responders in the hot zone need information to be simple and easy to understand, e.g., a set of objectives of the search plan or location information mediated through maps. Such organized information enables responders to understand the the plan, and maintain situation awareness. Information in the hot zone is collected and shared through different artifacts, these artifacts need to be portable and efficient, to ensure that the artifacts do not hinder the responder.

if it is too big or too heavy, it is already a burden, and if it can not stay powered up for 12 or 24 hours, it is not going to work... and if I'm in a remote location that does not have connectivity, again now it is useless. [P2]

Planners in the cold zone need detailed geospatial information, along with information from a human perspective, such as live feeds, videos, and images. These rich information sources are displayed and analyzed on large digital and paper maps (Figures 8) and tabletop devices [56], enabling collective sensemaking and planning activities. During Hurricane Harvey, responders in the cold zone collaboratively collected information from regions of Houston, Texas to determine which areas could experience flash and ravine flood hazards and what resources are needed. Such information includes the SAR branches responsible for each area, the information they collected on potential dangers, the levels of SAR operations that have already been performed, and any videos and photos of the impacted areas. All of this information is represented through large color-coded maps that are printed out (Figures 8) and photo collages that responders collaboratively use to develop operational plans that are then communicated to responders in the warm and hot zone.

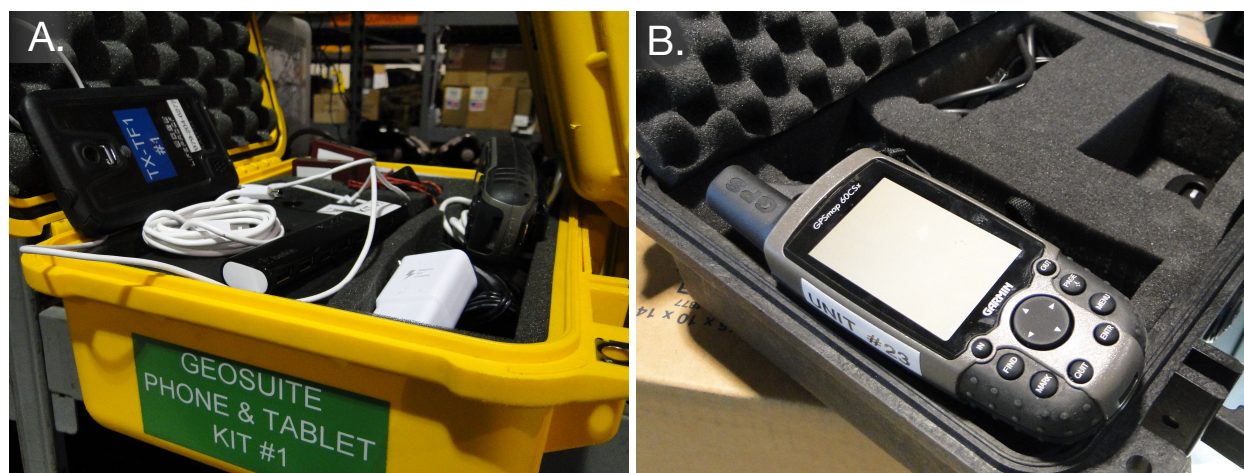


Figure 6: Advanced tools used by SAR responders for outdoor navigation, information seeking, and planning. A. and B. Digital maps on smart devices used for real-time location updates and placing standard GPS waypoint markers during SAR operations (see Figures 4). All photos taken during a visit to Texas Task Force 1 headquarters in College Station, Texas, USA. (Photos taken © Sultan A. Alharthi).

Information seeking and physical search methods and techniques vary throughout the stages of a SAR operation. These physical search methods are performed during SAR operations to collect different levels of information that can help plan the rest of the rescue operation [128]. Search approaches include: (1) *Preliminary survey (not search)*: assessing structures and safety of an affected area; (2) *Rapid search*: fast search of areas likely to contain victims; (3) *Primary search*: 360-degree check on the exterior of every structure, and may include a quick interior search; (4) *Secondary search (low)*: systematic of the interior and exterior of every structure; (5) *Secondary search (high)*: exhaustive and complete search of an affected area; and (6) *Targeted search*: priority search at a specific location requiring immediate attention.

Approaches are selected and combined based on the stage and severity of the incident and the availability of the information and resources needed to be able to develop an effective rescue plan [128]. Such search methods are mediated through tools, which are developed, modified, and abandoned within this ever-changing socio-technical activity.

Artifacts such as stake flags (Hansel and Gretel⁷) (Figure 5, B.); compass (Figure 5, A.); sketch maps (Figure 7); paper maps (Figure 8); and digital maps on smart devices (Figure 6) mediate navigation and search activities, enabling both spatial and temporal information seeking. The type and amount of information collected through these artifacts and shared to the different responders can be overwhelming. Skill at navigation and map reading help responders interpret these complex geospatial data sources [12, 128].

⁷A technique for leaving behind a trail of flags to find the way back, based on the folk tale “Hansel and Gretel”, in which two children dropped crumbs of bread to mark their trail so they could return home [25].

Within SAR training, students are expected to be confident in using a variety of techniques for navigating, searching, annotating, and mapping to collectively make sense and plan operations (Figures 4, 5, 6, and 7):

If I give you a very advance topographic map with tons of coordinates and altitude and all the water features and the 500 stuff⁸ on top of that it is very hard to understand, if you do not understand the basics of a map. [P2]

Tensions arise from the differences in how SAR responders perform search activities and use different tools. For example, in situations when digital tools or mapping software fail, responders switch between tools:

I just got back from Puerto Rico [where Hurricane Maria hit], no technology there, no cell phones, no texting, no electricity... we also went to Harvey, and some of that stuff [network] was down so we had to go back to the old method of pen and paper... you still got to be able to revert back to that and not get so dependent on technology. [P1]

Being able to transition between advanced tools and techniques (e.g., navigating with GPS) to the most basic is an essential aspect of SAR. When these basic and advanced techniques are combined, responders are able to enhance how they work and are prepared for complex incidents:

Combining both the old fashion pen and paper maps with the new technology is ideal. [P5]

⁸These types of maps represent in detail different land characteristics and show a variety of information, such as contour lines, latitude and longitude lines, terrains, lakes, roads, railways, man-made features, cartographic symbols, coordinate systems, and more can be overlaid on top of the map [12, p.104] (see Figure 8).

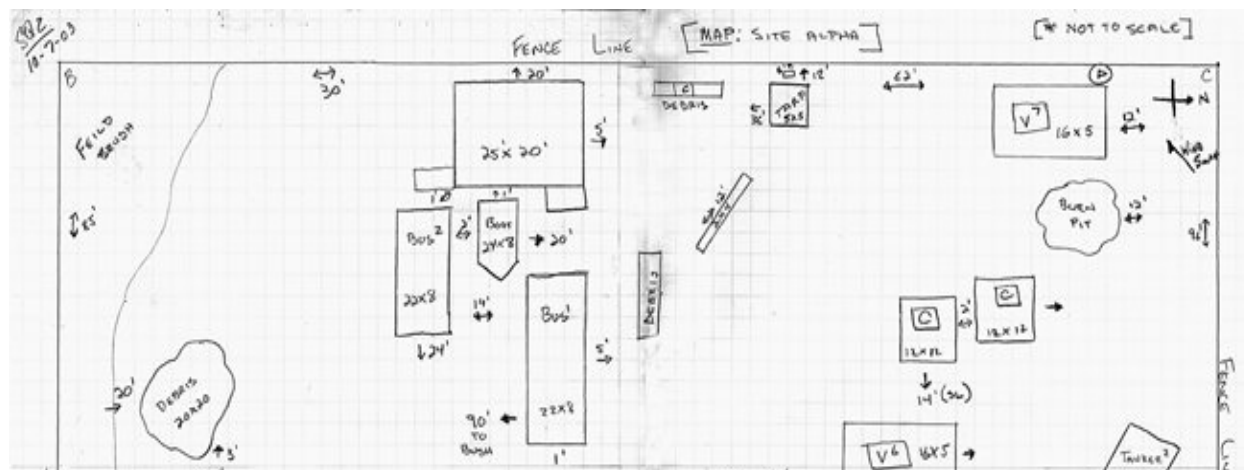


Figure 7: During SAR operations, responders engage in different basic map sketching activities to establish plans. Developing a sketch map is an essential skill needed for communicating planned activities. (Photo taken © Sultan A. Alharthi).

7.2 Cartographic Interaction as Collaborative Planning

Once information is collected, it is recorded, shared, filtered, and transformed into actionable intelligence and objectives. Each moment of transformation helps responders collaboratively create plans for different rescue and mitigation operations. One SAR member noted that:

we turn [information] into “SMART” objectives, we start building our initial action plan that includes...the objectives of the AHJ and leadership...our simple communication plan: for command purpose you talk like this, for tactical purpose you talk like this,...here are the medical plan,...any relevant rules of engagements or additional information from AHJ...allow the AHJ understand what our plan and next operations going to be, and allow our responders and leadership, and member know what is expected from them and what the goal is for the next operation [P1].

These plans are then shared with all SAR responders and stakeholders. Responders usually turn these actionable intelligence into plans that clearly outline a set of objectives that can be accomplished, taking into consideration the changing situation, circumstances, and available resources [12, 126, 128]. Objectives should adhere to **SMART** [P1], [41] which indicates that good incident objectives should be: (1) *Simple*: short, precise, and unambiguous; (2) *Measurable*: accountable, quantify SAR efforts to determine the effort an objective needs and *if* it can be achieved; (3) *Actionable*: action-oriented describing expected outcomes; (4) *Reasonable*: achievable with what is available; and (5) *Timely*: considers the time-frame for achieving objectives.

While SMART is a well-known management approach [38], and has been shown to be effective in other contexts [20], such an approach within SAR has not been studied. A consequence of SMART is that SAR plans are treated as *object-directed actions* [92] that are

situated within social, contextual, spatio-temporal, and cultural boundaries and rules [14]. Within such activities, deliberation between responders and stakeholders is essential to develop plans. While responders are members of the same community, subject to the same rules and division of labor, and are acting on the same object, they interpret information and create plans differently. Each responder brings different resources, skill sets, and artifacts along with unique mental models of the affordances and constraints of these artifacts [63, 104]. Tensions and potential contradictions can arise from the differences between and within communities.

The formation of the map post-recon: The result of initial reconnaissance activity is the formation of a **map** that has survived the potential contradictions of the initial reconnaissance processes. This is the central artifact commonly used across all responders and communities involved with the response. Maps mediate both individual and collective information seeking and planning activities. This can be seen during the initial survey of an impacted area, when individuals and teams use the available information to set up objectives and plans. Information collected during reconnaissance is communicated through the map artifact [56, 77, 115, 122], a mediating tool, that is created, modified, and shared, as the basis of collaboration and planning:

we consult the map given to us by Incident Base, which outlines the search plan [P7].

SAR responders need to constantly know where they are, where they need to go, and how to get there efficiently.

Map as space of technological tension: SAR team members use a variety of outdoor navigation methods and fluidly move between mediating tools (e.g., paper or digital maps). Such activity is influenced by the conditions of the situation (Figures 6 and 8). The variance of response needs is a unique space, as the availability of data access is as such that computationally-mediated products may *not* serve well. As a result, we observed that understanding

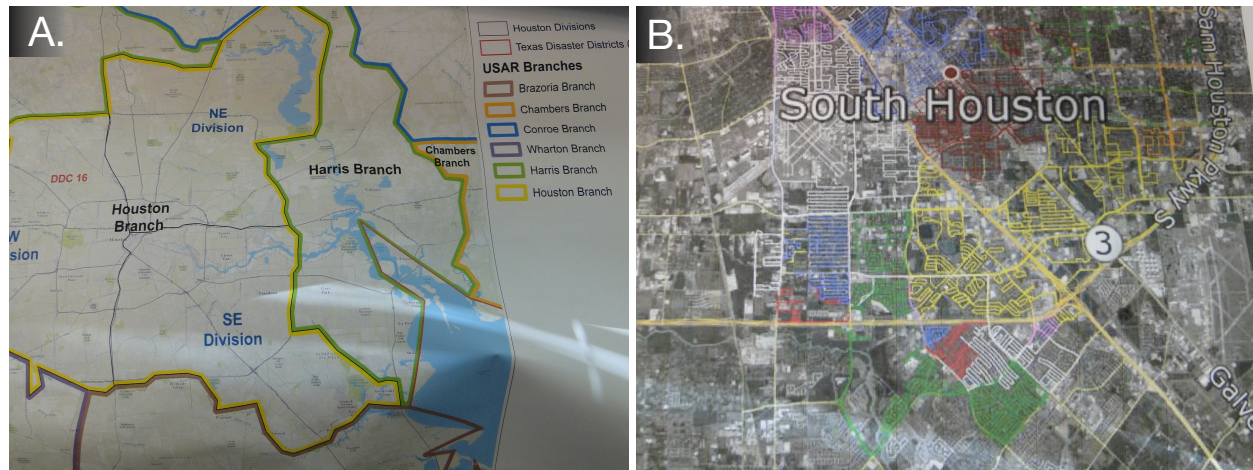


Figure 8: Different types of maps of Houston, Texas, USA from search and rescue operations during the 2017 hurricane Harvey. The different maps show information related to the different operations. A. The map of Houston, Texas is divided into multiple regions representing the overall disaster district (outlined in red), subdivided by which SAR branches will cover the areas. The map here shows overlay information of potential areas that can experience flash and ravine flood hazards. This map is designed for planning purposes and to provide situation awareness about potential risks. We notice the use of free-hand annotations and drawing on maps to highlight part of the map during the planning process, which help reinforce a shared common grounding of their strategies [35]. B. A map annotated with color coded GPS data representing the different levels of SAR operations performed during the operations, which help responders keep track of the operation plan and synchronize their effort in real-time. All photos taken during a visit to Texas Task Force 1 headquarters, College Station, Texas, USA. (Photos taken © Sultan A. Alharthi).

the most basic, non-digital techniques of navigation, mapping, and cartographic interaction is critical in SAR planning.

typically they start [training] at the basic level, here is a map,...here is a map and a compass,...here is a compass and no map,...here is a compass and a GPS,...here is a GPS, because you got to understand the most basic thing for the most complicated thing to make sense. [P2]

Cartographic interaction is central for sensemaking and planning activities, in which responders interact with and collaborate over some sort of map and using geospatial information. Thus, the ability to understand, create, use, modify, and share such information and artifacts is a key activity in SAR.

7.3 Artifacts Influence Collective Sensemaking & Planning

Artifacts play an important role in both mediating and stabilizing a SAR operation activity. According to interviewees and notes from the training courses, the map serves as a representation of the initial SAR operation reconnaissance. In this section, we also address the map's relationships to upcoming technologies like drones and wearable computers. There are six ways that maps mediate SAR activities:

- (1) identify the main location of the incident and establish the zones of operation and search areas;
- (2) locate and identify accessible and safe terrain;

- (3) develop and communicate plans through sketching: developing a well-drawn sketch map is essential for communicating your planned activities.... [It] is a good way of displaying your plan and good documentation of your actions. [128];
- (4) transmit information related to the incident (e.g., areas that are covered or not covered), to responders and command;
- (5) navigate search areas and orient operatives; and
- (6) maintain situation awareness: maps describe the progress of the SAR operation: I'll know where I'm on my map, I'll know where I'm within my segment, and I'll know where my other responders are near me... I'm not just searching randomly, but I'm specifically looking for this individual in this address, or someone previously have dropped a spot [on a map] and said this is the last know spot that individual entered the water... I can see we are about to hit the warm zone to this hazmat. [P2]

Other technologies that came up in our interviews are of potential interest to HCI-oriented work in this space.

Drones: Participants even noted that drone use would dramatically change SAR. Drones are being increasingly used to provide great value to SAR operations and disaster response, in general [68, 138]. As these scenarios materialize, there will be a need for innovative training in which drones are integrated into SAR as a main artifact.

I used the drones in New Jersey, in a train wreck, and it was unbelievable, the real time and the situation awareness you can get the whole big picture [snaps fingers] in two minutes, even if I got out and walked it, it will take me 20 to 30 minutes...I was able to get the big picture and know what exactly was going on...I think that drones going to change [SAR]... [P1]

The previous quote is becoming less associated with, “going to change SAR” and more associated with, “is changing SAR.” For example, drones were used during Hurricane Harvey in summer 2017 and more recent hurricanes. Drones were used to create 3D maps of the flooding and the damage in a very short time, which helped SAR operations [103]. Such tools can help to shorten the time and reduce the effort needed for responders to collect enough intelligence for rescuing victims:

get out far enough - fast enough and you will be more successful...adrenaline in their [victims] system will move them further away and they will survive longer than we can imagine. [P6]

In such complex spatio-temporal activity, fast and effective information seeking, mediated through advanced artifacts, can positively impact SAR planning. While drone advances are promising, they come with their own challenges and tensions. It seems obvious that one of the main challenges in adopting its use and other technologies are: “weight, size, power, connectivity, and cost” [P2]. Additionally, training is required and regulations and rules impact how such artifacts can be used. For example, information overhead [93] can be caused by the huge amount of aerial photography from drones [84]. Instead of providing help, they can become a burden. Sorting, filtering, and sharing such large amount of information is non-trivial [75], which can negatively impact how responders make sense of an incident. Disaster management systems [57, 121, 135] and information visualization techniques [140] need to enable responders to easily make sense of the abundance of information and enable seamless use of such information within the existing planning practice. However, sharing information, especially aerial pictures and videos, of the impacted areas with other SAR communities or the public raise a number of ethical and privacy tensions [2, 32, 85, 139], that responders need to take into consideration when performing these activities.

Differences in what is allowed or accepted between SAR communities can cause tensions. Thus, incorporating differences in information seeking methods and artifacts within SAR training is an essential step that are starting to be encouraged [83, 112].

7.4 Influence of Rules, Community, and Division of Labor

Tensions manifest themselves as differences in the rules, expectations, and available artifacts within and between SAR communities, influencing the activity systems as a whole. Each SAR mission is unique; there are specific rules that govern how responders go about creating plans and operating:

[know] the expectations and rules of the AHJ before you jump there and start doing stuff. [P6]

Such rules differences influence *which* artifacts can be used to perform the SAR activities. For example, when conducting a physical search, a number of artifacts (e.g., stickers, spray paint, GPS markers in digital maps (Figures 4)) can be used for tracking status, including marking buildings and areas that have been searched, safety determinations, and victim status:

the AHJ do not want you to spray houses, you need to use stickers. [P3]

In these situations, responders need to understand the rules imposed by the local authorities and their SAR community. These differences can influence SAR community hierarchy and division of labor. We observed that the organization of SAR work is not always fixed; it may change with each incident. Responders deployed to Hurricane Harvey reflected on tensions raised and how they changed the organization:

in hurricane Harvey, while the county judge were the lead, TEEX [Texas A&M Engineering Extension Service] was the lead agency for [SAR], and coordinated all the [SAR] responses in Texas, even when the federal government came in, it fell under TEEX, who then supported the county, so it was an almost inverted organization chart where sure these big agencies and the DoD and the military FEMA where coming in, but it actually all goes down to supporting the local jurisdiction. [P2]

Responders move in and out of SAR communities continuously. When new responders come into the community, the practice, expectations, and artifacts may change. Emergent generational gaps between responders can influence how they work together and use artifacts:

as the advance of electronic data maps on phones and people using GPS, that skill [outdoor navigation] becomes lacking, so simple paper maps for younger generation are becoming more difficult to understand. [P2]

I’m a pen and paper guy, other guys use their cell phone to keep their notes, I do not type that fast, and I do not text very often...[young responders] were able to take that technology and implemented into a plan, and implement it into a rescue, but there is going to be a learning curve, for most of the younger responders, it is second nature to them, it is the older responders that have to learn to incorporate those stuff [technology] in their work a little better. [P1]

The above insights increase our understanding of the difference in information seeking and sharing, and how rules and differences in practice and training between generations of responders may impact SAR. Further research that focuses on the generational and training gaps between responders and how it may influence SAR activity, is needed.

8 DISCUSSION & DESIGN IMPLICATIONS

We apply our analysis and AT framework (Figure 3) to the design of future information technology to support SAR, as well as training. In SAR, the hybridity of activities, settings, roles, rules, and the need

to analyze a large amount of information to create effective plans raises a number of tensions. Our analysis enabled us to understand the rich contextual factors influencing SAR work and training and identify key tensions within and between SAR communities. Current SAR systems and training have little support for these tensions in this complex work.

Our findings suggest that information seeking and reconnaissance are a central part of SAR training. There are differences within SAR communities on how to mediate these activities. The type of information needed in the operational zones differ, requiring different ways to handle and visualize such information. Our findings, critically, point to the importance of geospatial information during the SAR planning process – the creation and manipulation of maps is central. Remote interaction and collaboration will always pose problems, which suggests that new and innovative solutions are needed, especially as new tools, technologies, and sources of information are adopted by SAR communities.

We argue that the tensions that arise serve as a source for design and as requirement for improvement. In the following, we develop design implications for systems that will support SAR in the field or enable training systems to simulate essential components of work practice: mixing physical and digital mapping; mixing individual and collective mapping; building for different levels and sources of information; and building for different rules, roles, and activities. Such implications support and teach SAR responders how to perform information seeking, make sense of situations, share information, collaboratively plan, and use information artifacts effectively, including mapping and navigation practices in the outdoors.

8.1 Mixing Physical & Digital Mapping

Our analysis showed that disaster responders use physical and digital artifacts interchangeably, as each mode offers its own affordances and constraints. Paper must always be carried and serves as a backup, while information technology is valuable for its ability to pinpoint locations. Responders might have multiple maps of each type, each with its own style, information, annotations, etc. (Figure 8).

Transitioning between modes is not seamless: relevant data must be manually mirrored among media. This manual transition of data makes it time consuming and highly prone to human errors. Our results pointed out differences in the type of data that can be collected by responders and how it should be handled, which adds another layer of difficulty. These challenges call for more automated approaches to process, organize, and share data and information through both physical and digital modes.

Designed future systems would usefully draw on *mixed reality* [17, 18, 23, 119] as a way of considering how to connect physical and digital data. Approaches might consider this failure-prone need to transfer data across media as an opportunity for seamless design. *Seamful design* considers how user experiences can incorporate seams – failures of technology to support a task [17, 30, 31] – while still delivering an effective experience. Approaches to capturing and translating data across media automatically (e.g., using computer vision to pick up essential map components from a hand-drawn map or augmenting a paper map with digital data), while remaining

flexible to human manipulation, are essential to easing the burden on human operatives.

Training systems need to ensure that responders gain experience and practice in making these transitions, as they are nontrivial. Learning to filter, transform, and copy information carefully between modes is an act of distributed cognition [69, 131]. To do so, collaboration support systems need to consider how they can be designed to support the activity of easily transitioning between modes. Again, mixed reality is useful here, enabling, for example, physical artifacts, such as paper maps, to be augmented using shared digital information [56, 97] to enable effective learning of different mapping and navigation methods.

8.2 Mixing Individual & Collective Mapping

We observed that individual and collective mapping is central in SAR work. Responders collect information from reconnaissance missions, use maps to navigate and keep track of plans, and share the information they collected individually with the rest of the team. Navigation and geographic information systems (GIS) rarely enable both individual and collective activities. However, large-scale planning activities typically involve multiple individuals and teams working together and collaborating through such navigation and GIS systems. The resulting maps become the basis for collaboration and planning as pointed out by our results. Thus, such systems need to assist individuals and groups in working together effectively by helping them identify areas for search, keep track of remote information, and increase awareness among individuals and teams.

The ability to overlay and update information on maps is a key activity in SAR [56]. In many cases, responders are deployed to places where the ground truth no longer matches existing maps [122]. Responders need to situate themselves, identify still-existing landmarks, and update records (e.g., marking missing structures and possibly removing them from the map). Systems need to enable these acts of cartography and the ability to represent spatial information layers. Providing annotation interfaces (e.g., markers and waypoints (Figure 4)) helps ground information in physical space [10, 133]. SAR responders need systems in which they can easily update, annotate, remove inaccurate information from, and share maps.

To support SAR training, developing reconnaissance and sense-making skills, systems need to enable both individual and collective activities to enforce the need for cooperative work, fostering social interaction, and learning how to establish common ground [37]. Information collected individually needs to be shared and combined to enable collective sensemaking and planning. Intelligence relating to building identification, conditions and hazards, and victim status need to be posted in a standardized fashion.

8.3 Build for Different Levels and Sources of Information

Plans rely on the right inputs from diverse sources at the right time. Differences in information richness [39], needs, and representation within SAR communities and the operational zones (i.e., cold, warm, hot) need to be taken into design consideration. While prior work points to issues of work under high information uncertainty [56, 131], we observed in our study that uncertainty can be caused by

differences in how artifacts are used in different operational zones, how rules influence the use of artifacts, and how generational and training gaps may impact situation awareness.

Differences in collecting and visualizing information is critical within SAR work. New techniques can be designed to help responders seamlessly [30, 31, 61] access different types of information from different artifacts. For example, our results showed that, in different operational zones, responders use different artifacts, such as table top maps, large displays [72], small handheld devices, or paper artifacts. Information and plans shared between these different artifacts need to be seamlessly accessed by all response teams, reducing uncertainty of information. Tools could be designed to accommodate the differences in how responders collected, store, and share such information.

Support for Aerial Reconnaissance: SAR systems and training can support *aerial reconnaissance* [116] to reduce the risk for responders and make their work more efficient. Adapting or establishing aerial search methods (e.g., primary or secondary search using drones) is critical to ensure that both ground and aerial search efforts complement each other for better information seeking. When such information is collected, it can be livestreamed and made available to responders to use in making sense of the situation, develop plans, and relay intelligence to the rest of SAR teams [84], however, ethical considerations need to be recognized when using such data (e.g., classified locations, victims' bodies).

Support for Social Media Reconnaissance: Enabling *social media reconnaissance* provides responders with initial data, such as data from microblogging platforms (e.g., Twitter), that can be visualized to help responders create initial understanding and collectively make sense of incidents [29, 40]. Although a large number of research efforts investigated the use of microblogging data in disasters (e.g., [29, 40, 60, 113, 137]), such data is currently not integrated with SAR. Designers need to focus on integrating such emerging sources of information within these systems and training [106].

8.4 Build for Different Rules, Roles, & Activities

Practice involves a constant transition among different roles and activities, with concomitant shifts in unity of command. Our AT analysis showed how responders' activities are influenced by rules that govern how SAR is performed. Such rules need to be imposed and be visible to the subject when pursuing an activity so that the division of labor is clear. When rules constrain the different activities that responders can perform, or the type of artifacts they can use, they are no longer dependent on one way of performing their tasks, they are able to easily adapt to changes within SAR activities.

Subjects can have different roles, depending on the specific activity in hand, which enable the development of skills in transitioning between SAR roles, and understanding the different organizational levels of authority. Training systems need to focus on supporting activities performed and address how each individual activity is part of a larger social system. Our study of SAR work and training calls for more attention to integrate *activity-centered design* [50, 62, 80], in which systems and training can focus on supporting

both micro and macro activities that can take place within SAR contexts.

9 CONCLUSION & FUTURE WORK

In this paper, we wanted to answer a question, "What are the informational components of SAR practice and how is information recorded and communicated?" In order to answer this question, we contextualized the practice of SAR using activity theory. SAR is seen as a sensemaking activity mediated by training, artifacts, and above all, maps. Within this activity is a complex, inter-connected set of tools, subjects, objects, rules, communities and divisions of labor that require quite a bit training, training that is potentially in need of more hybridity. We expect a gradual uptake of information technology by SAR in general but direct intervention in training and in practice will help to shape that uptake. As a result, the answer to our research question is aimed at helping HCI researchers understand this space so that they can begin to shape information ecosystems, software, and hardware that are adopted over time.

One of our most powerful discoveries is that while SAR does not incorporate many information communication technologies, the use of maps is an important source of information in the practice of SAR that can be digitized in an effort to widen the number of eyes participating in the act of search and rescue. If we identify how SAR responders collaborate, how information is collected and communicated, and how we can best design for future collaborative mapping systems, HCI can help support SAR operations.

That support must meet how SAR responders work collaboratively with maps as they engage in cartography in the field and in the base. Mapping is an emergent function for sensemaking and how it involves adding and removing information, as well as providing alternative views. In terms of these future information systems, maps are a sensemaking tool that have a number of vectors to not only design interfaces for, but invite others to view, edit, and search.

While the map is a vector of digitization, it is not a simple task. The complexities of the organization of SAR – with the involvement of multiple agencies, each with its own rules and practices – means that there is a constant need for responders to consider information from an organizational perspective, undertaking map-making, and other activities, accordingly. This leads to needing alternative information views that prioritize different needs dependent on proximity to the disaster at hand; these views have different tempos and so, different expectations for performance, speed, and affordance. The need to transition maps between paper and digital modalities is a challenge, one that might be addressed through careful mixed reality designs. Other technologies like drones could also be made an essential part of the SAR process as long as they too, are a part of the information system surrounding cartography.

9.1 Future Work

The design implications outlined in the present research will support building collaborative information technologies for the field. Each implication calls for more attention to integrate new sources of information and collaboration within the design of SAR systems and training. In future work, we expect to put these design implications into practice, for example training exercises in mixed reality environments can provide better representations of the field. Prior

design fictions have outlined one such a system [87] and we hope to develop the tools and training needs associated with it in the future. Further, while current technologies are not yet up to SAR operatives' standards, we expect development to push them into a ready state for this harsh, sometimes dangerous environment.

9.2 Limitations

This work adds to a growing body of research on disaster response practice (e.g., [56, 68, 76, 77, 110, 122]) and sheds light on SAR sensemaking and planning. We acknowledge that this work is limited, and not intended to provide an exhaustive analysis of SAR work and training. The focus of the present work is centered on providing a foundation for understanding current SAR work and training in regards to collective sensemaking and planning. Observing actual SAR is difficult for many reasons [8]. Naturally, observing actual SAR practice might lead to different findings, which is a limitation to this work. Also, the interviews and surveys focused on a limited number of SAR responders within the USA. In order to overcome these weaknesses, we triangulated using other sources of data and methods of analysis. As a result, we present a significant first step in understanding SAR. Conducting more studies with responders will provided a broader, more complete, view of SAR work and training. While our findings suggest a number of design implications for SAR systems and training, they must be viewed within these limitations.

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