Implicit Coordination in Firefighting Practice: Design Implications for Teaching Fire Emergency Responders

Zachary O. Toups, Andruid Kerne
Interface Ecology Lab | Computer Science Department | Texas A&M University
College Station, Texas 77843, USA
{toupsz, andruid}@cs.tamu.edu

ABSTRACT
Fire emergency response requires rapidly processing and communicating information to coordinate teams that protect lives and property. Students studying to become fire emergency responders must learn to communicate, process, and integrate information during dangerous, stressful, and time-sensitive work. We are performing an ethnographic investigation that includes interviews with experienced fire emergency responders and observations of team burn training exercises with students. We distill salient components of firefighting practice, which are relevant to the design of fire emergency response education systems. We derive design implications for systems that teach fire emergency responders to deal with issues surrounding the communication and integration of fireground information: the mixing of communication modalities, the distribution of information acquisition sources to create information differential and uncertainty, and audible clues.

Author Keywords
Firefighting, emergency response, ethnography, team cognition, distributed cognition, implicit coordination.

ACM Classification Keywords
H1.2. Models and principles: User/machine systems, Human factors.

INTRODUCTION
Fire emergency responders (FERs) work in dangerous, dynamic environments. The success of communication and coordination can mean the difference between life and death. Fire emergency response is based on real-time information flow: radio and face-to-face are essential communication modalities. The ability to optimally utilize and manipulate these channels is an important skill, which is learned through experience. FERs use complementary communication modalities, well-defined roles, and shared experience histories to implicitly coordinate their actions. Team structure and strategy is designed to optimize coordination, information gathering, and sensemaking.

We are conducting qualitative research into the work and education practices of FER professionals. To understand how they perform distributed team-based tasks, we have interviewed expert FERs and observed burn training, a simulation in which students enter special burning buildings to search for victims and put out actual fires. We are investigating needs and requirements for FER education systems, based upon how information flows within these teams.

We present findings from an ethnographic investigation of FERs. First, we discuss background, including how firefighting is conducted in terms of team topology. We conduct interviews with experts and observe burn training exercises, present analysis of how information flows in fire emergency response work practice, including how this leads to emergent behaviors and affects team cognition. Finally, we develop recommendations for systems supporting the education of FERs, in order to promote learning to implicitly coordinate their own situated actions [16] using the information flows available to them in the field.

BACKGROUND
The relevant background is diverse. In this section, we discuss the conceptual frameworks of distributed cognition and team cognition, and how these relate to firefighting teams. We also give an overview of prior computing systems and designs that have been developed for supporting FERs. Finally, we discuss how FER teams are structured in order to maximize distributed and team cognition capabilities.

Distributed and Team Cognition
Distributed cognition is a theoretical framework for investigating how information is coordinated within systems of people, artifacts, and environments [8]. It considers how this information flows between participating entities. The entities and the information upon which they operate form an integrated whole.

We apply distributed cognition in the context of teams of people that interdependently work together to achieve

CHI 2007, April 28-May 3, 2007, San Jose, California, USA.

goals. This is known as *team cognition* [12]. An important component of team cognition is *implicit coordination*. Mutual understanding is achieved without explicit communication, enabling team members to better use cognitive resources to accomplish tasks [12, 15]. Methods have been developed for measuring implicit coordination through a team's *anticipation ratio* [6, 12]. This ratio compares the number of remote communications that supply information to the number of requests; it is measured on a per team-member basis [6, 12]. The anticipation ratio indicates how well the information needs of each member are being anticipated by other team members, that is, how well they can get what they need without asking [6, 12].

Implicit coordination is important for teams that work in dynamic, stressful environments because it reduces *communication overhead* [12]. Communication overhead, the cost of using a shared communication channel, inhibits the team's ability to work because it increases the cognitive load of members and saturates the bandwidth of the shared communication channel, which might be used for other purposes [12]. It is clear that implicit coordination is a hallmark of good fire emergency response teams:

> *You get a good crew that works together all the time and they can do things that just by gestures, body movement, and all that. You can communicate with each other without saying a word; you know what's going on* [P3].

Shared mental models and situational awareness are constructs that support team cognition, enabling autonomous operation within the team and reducing communication overhead. *Shared mental models* allow team members to fill in gaps in their knowledge about what other team members are doing by modeling action and status in their heads [6]. This, in turn, reduces the amount of explicit coordination that is necessary to keep the team synchronized. Shared mental models directly contribute to situational awareness [5, 6]. *Situational awareness* denotes what a team member knows about what is going on around her/him and ability to predict future states of the situation, both locally and globally [5]. It is critical for individual and group decision-making as it allows independent reasoning about the situation, improving implicit coordination [5].

Systems and Designs

Prior systems have addressed support for FERs. Landay's group designed prototype systems for supporting incident command displays and location-aware mobile systems for FERs [9, 10]. These designs were based on an ethnography of the work of incident commanders [9, 10]. Dugdale et al. performed an ethnography examining the role of face-to-face communication in fire emergency response for increasing immersion in virtual environment training simulations by adding expressiveness to avatars [4]. Landgren explored how firefighters communicate and the temporal flows around their work [11]. His work presents design implications for information systems supporting FER accountability by addressing the ephemerality of voice communication [11].

Team Structure: Roles of People and Technologies

We integrate prior research with expert descriptions (see Table 1 for more information on the participants, labeled P1-P6) to develop understanding of the roles in FER teams, the interaction of formal and informal relationships, and the relationships between roles, technologies, and practice. A key component in the practice of firefighting is that it involves the coordination of distributed, well-defined small teams, called *companies* or *crews*. While companies are highly structured, these structures are not rigid. High levels of experience, training in the performance of multiple roles, and shared mental models enable the roles of individuals within a team to be dynamically reassigned as the situation warrants. In the course of situated practice, deployed, low-ranking officers sometimes use local knowledge to override decisions from supervisors, inverting the command structure.

For any incident, as many as five FER companies, an ambulance, and the battalion chief may be deployed, before there is a call for reinforcements [P3]. The term "*incident*" refers to any event that requires emergency responders to prevent loss of life and/or property; more specific is "*fireground*", indicating the area where FERs are operating [2, 19]. Teams in the field are organized hierarchically, with an incident commander at the top and individual firefighters at the bottom (see Figure 1). We will describe these team topologies from the bottom up to prevent confusion. Note that the structure discussed here is for small incidents; the *Incident Command System* provides methods to scale up the structure to provide for other types of officers, more diversification of jobs, and cross-agency cooperation in more complex situations, such as major disasters [2, 19].

Radio is a critical component of fire emergency response for FERs working distributedly, while face-to-face communication is used whenever possible. Each firefighter carries a radio with them while at the fireground and these radios are used to communicate when not collocated [3, 19]. Each incident uses only one channel for radio communication (although very large incidents may use multiple channels). Radio communication is carried out in plain English, using a shared vocabulary of specific, concise terminology [2]. This precision allows communications to be quick and to the point, reconciling meaning immediately, which eases the FERs' cognitive overhead in interpreting what is said [6]. The

	Age	Experience (years)
P1	28	Firefighter – 6
P2	48	Firefighter – 30
P3	37	Firefighter, Firefighting Instructor – 18
P4	34	Firefighter, Engineer / Driver, Aircraft Rescue Instructor – 14
P5	42	Firefighter – 31
P6	39	Firefighter – 20

Table 1. Interviewees.

communication needs for FERs have driven the way they are organized, allowing them to use face-to-face communication whenever possible (because it is more expressive) and radio when necessary.

Companies

The lower part of the fire emergency response hierarchy consists of companies. Each company is typically a group of three to four members: a company officer, one or two firefighters, and an engineer/driver (who is outside the scope of this paper), although an increased number is possible. In the course of responding to an incident, a company is strongly associated with a particular *apparatus*, a vehicle used to fight fires. The type of apparatus used determines the company's role at the incident and the corresponding tasks performed by its members [P4]. There are two main types of apparatuses used in firefighting: fire engines (vehicles equipped to put out fires) and rescue trucks [P2, P3, P4]. In addition, ambulances play a primary role at any incident [P3, P4], but they are beyond the scope of this paper. Note that there is considerable variance in the capabilities of these apparatuses, and some stations employ more specialized vehicles, such as those that deal with hazardous materials or aircraft fires. [19]

The development of multi-story buildings drove the need for rescue trucks with ladders, resulting in a diversification of FER roles [19]. With role diversification, all FERs are *cross-trained*, that is, they receive education in rescue, fire attack, ventilation, and emergency medical care [P2, P4] [19]. The role they perform at a specific incident depends on which type of apparatus they ride. Officers generally have more experience and may have received command training [P4]. Cross-training has the advantage of allowing personnel to be dynamically reassigned as the situation warrants, similar to plug-and-play teaming [7], as well as improve their ability to understand what one another are doing and form shared mental models [6, 12].

A *firefighter*, the lowest rank in fire emergency response, may perform one of two primary task sets, depending on the apparatus to which he or she is currently assigned. Firefighters working on fire engines are tasked with putting out the fire and preventing its spread, while those working on ladder trucks perform ventilation and rescue, and provide a path for other firefighters to the upper levels of a building. In the course of actual practice, these roles shift depending upon circumstance; for example, a firefighter who has gone into a house to put out fires may need to ventilate the floor s/he is on. Note that firefighter is an incident role, as well as a job, and the company officer, if necessary, may also fill that role. [P2] [19]

Firefighters entering a structure are required to work in groups of two or more; they must always enter and leave a building together [3]. In the case that a company has only one firefighter, the company officer will enter the building with him or her [P1, P2]. In addition, there must be a rapid-intervention team (RIT) available at all times [P6] [3, 17].

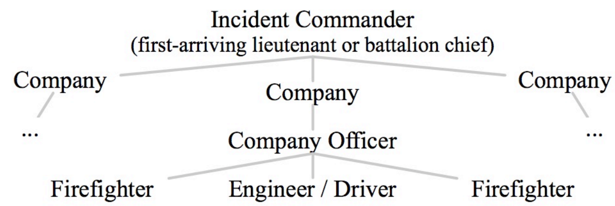

Figure 1. Topology of fire emergency response teams.

The RIT is a group of FERs who wait outside the building specifically to quickly enter and rescue the original group if it becomes necessary [P6] [17]. Because of these regulations, at least four firefighters must be available before anyone can enter a burning structure (two to go in, and two to be the RIT).

The company officer commands the other three members of the company. The officer monitors the situation from outside for the firefighters and works to ensure that they are safe and accomplishing the objectives for the incident. The officer maintains radio contact at all times and may be called upon to fill the role of firefighter. [P1, P2] [19]

Incident Commander

Incident commander is a leadership role at an incident [2, 3]. The incident commander is responsible for mediating the strategy for the situation, coordinating outside resources, and ensuring the safety of the team [P6] [2]. The role is that of "*...observer and communicator...*" [P6]: he or she monitors the overall situation and communicates to the companies about his or her observations, knowledge, and strategies. In addition to coordinating the deployed personnel, the incident commander must mediate communication between the fireground and the outside world by calling for reinforcements, ordering resources, and working with other agencies, such as the police and power companies [P2]. Incident command typically transfers once, from the first-arriving officer to the battalion chief when he or she arrives (although certain situations may warrant a temporary transfer) [2, 3]. The incident commander may be in charge of any number of companies, while each company's officer is in charge of its emergency responders.

The battalion chief[1], the field commander for all of the companies currently on shift (the battalion), rides in a separate automobile outfitted with communication gear and various information artifacts [10, 19]. This vehicle is a mobile command post that is positioned one to two blocks away from the fireground [P1, P2] [19]. From this vantage point, the chief can get an overview of what is occurring during the incident, without getting in the way of the other emergency vehicles and personnel [P2]. The battalion chief has access to all information that is available, including preplanned strategies for attack and rescue, blueprints of the structures and areas involved, hazardous materials

[1] *Battalion chiefs* supervise emergency responders while *fire chief* is an executive office; the two are sometimes the same [19].

Figure 2. ***Left:*** **The back of the three-story prop; in this picture, firefighters are training inside.** ***Right:*** **Attack 1 has opened the front door of the three-story prop, and prepares to enter and fight the fire.**

inventories, and other relevant information, enabling the commander to perform his duties [10, 19].

The preconceived notions of team members' roles and duties constitute plans [P2, P3]. Individual team members know their jobs within the teams, but these jobs must be modified on the fly to account for changes in the environment that cannot be anticipated. Thus, situated actions play a significant role in firefighting practice. [16]

FIREFIGHTING PRACTICE – STUDIES

In this section, we discuss our fieldwork methods and data at the Texas Engineering Extension Service's Emergency Services Training Institute (ESTI). ESTI contains the largest live-fueled FER training field in the world, and educates over 45,000 emergency responders per year [18]. We have two main sources of data from ESTI: interviews with highly experienced FER professionals (Table 1), and observation of the education of students at the fire school (training sessions are labeled T1-T3 when referenced). The interviewees are local firefighter and instructors at the school; thus, we are collecting data from sources with very different levels of experience (see Table 1 and Figure 3).

In addition to teaching experienced professional and private fire emergency response personnel, the school also runs a program for new recruits. Students go through a twelve-week course and live at the fire school. During the course, they take classes and learn from books, but also experience practical, hands-on training using live fire and real equipment. In *burn training*, a particular form of practical experience that simulates emergencies, students are grouped into companies and sent to deal with life-like scenarios. These simulations are situated amidst *props* that replicate real situations in a theater-like manner that is fully functional, such as a three-story residential home, an industrial facility, a tanker truck, and an aircraft [18] (see Figure 2). Burn training uses real fire, in forms such as chemical liquid and bales of hay. The students must work together in order to put the fires out. The training is run as if it were a real incident: students ride in on trucks, set up command, organize teams, search for victims, and put out the fire. As part of their final evaluation, students are surprised out of bed early one morning with a simulated dispatch, requiring them to go from sleep to full readiness and deployment without instruction. Such training provides valuable experience similar to that encountered in the field.

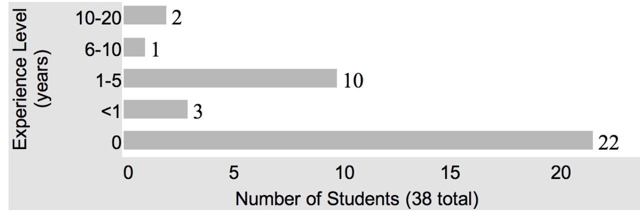

Figure 3. Levels of student experience.

Over the course of several weeks, we worked closely with an experienced instructor who is also the fire chief for a small community's volunteer firehouse. This informant explained the facilities and related personal experiences both as an instructor at the school and in the field as an FER. Through his guidance, we were introduced to several local fire emergency responders and instructors and allowed to observe a student training course in action.

Interviews – Experience Reports

The first part of our study consisted of interviews conducted at ESTI with professional FERs.

Methods

The interviews were partially structured, enabling the emergence of significant informal details about work practice, as well as the derivation of formal structures and processes involved in protecting people in and around residential and commercial buildings. Structured questions and spontaneous queries focused on communication and coordination practices in the field, especially how FERs work together and share information.

The six professional interviewees were highly qualified, and some serve as instructors. All were FERs with extensive field experience: five of them had between 11 and 31 years of experience (Table 1). They were all male, with ages ranging from 28 to 48. The identities of the interviewees have been kept confidential. Interviews were recorded to the audio tracks of digital videotape and later transcribed.

The investigator experienced the interviews first hand and recorded the audio from them. The interviews consisted of expert descriptions of fire emergency response work practice. Subjects explained how teams are organized and communicate, the methods they use to coordinate with fellow FERs, and personal stories about field experiences.

Observation – Student Burn Training Exercises

The second part of our study consisted of participant observation of students performing burn training exercises.

Methods

Observation took place on one training day during the eleventh week of student training: March 23, 2006. Three mock burns with 38 students were observed on the three-story prop: a concrete building that functions as if it were a three-story home (see Figure 2). The three-story prop actually has four floors: a basement, two levels, and an attic

[18]; in these exercises, the basement was not used. The prop is set on fire inside using burning bales of hay, and students practice firefighting and rescue in the building using dummies.

All three burns were experienced firsthand and videotaped from outside the building due to safety concerns for the observer and camera. The observer was provided with a guide for the first burn, an experienced student who was not directly participating in the training. He was also given a radio for all three, which was set to the same channel as those carried by the students and faculty. The video was recorded with the radio held to the microphone of the camera, so that the tape in the camera recorded what occurred in synch with the radio communication, in addition to first person dialogue and visible events. The audio was later transcribed.

DATA AND ANALYSIS

We examine several aspects of firefighting that have become clear through this ethnography: how information flows in fire emergency response teams, the emergent behaviors that firefighters make use of, and how team cognition works in these teams. We begin with a description of an observed event that exemplifies many of the aspects discussed later, and then describe how information flows within firefighting teams.

Example – Training Exercise Simulation

Police and residents report that a three-story family home is on fire. Engine 18, Engine 21, Ladder Truck 1, and Rescue Truck 22 arrive on scene, each shortly after the other. Four-person companies from the two engines and the ladder truck are labeled the three Attack teams by the incident commander, while two from the rescue truck are the Search team. Search 1 enters behind Attack 1 to perform search and rescue, while the others fight the fire on the first and second floors. Attack 1 manages to clear the first floor, and moves upstairs to join the other two, then moves on to the third floor, as there are reports that the fire affects all levels of the building.

Unknown to the firefighters upstairs, the fire has spread back down to the bottom story. Command notices the smoke and fire through the windows from the outside.

Command: *Attack 1, can you get back down to the first floor? There's fire showing on the alpha*[2] *corner of the first floor.*
Attack 1: *Attack 1. We're in there, try and see if you can pull *static* finish off this fire.*
C: *So Attack 1's on the third floor?*
A1: *Yes.*
C: *Attack 3, what's your location?*
A3: *Attack 3 to command. We're on the second story; we're running into the second crew in the stairwell that is already up on the third floor.*
C: *That's clear. Attack 3, if you're available, can you get down to the first floor on the alpha corner of the structure? There's fire showing.*
A3: **static* We'll have to exit the structure and go back in on the first floor. We came up on the second story exterior stairwell.*
C: *Alright, that's clear.*

Throughout this exchange, the fire is spreading. Already, almost a minute has passed since Command noticed the new blaze, and it could be weakening the floor, endangering the FERs inside. Attack 2 steps in:

A2: *Attack 2 to command.*
C: *Command here.*
A2: *I've got some firefighters here, do you want them to pull the speedlay*[3] *off and knock the fire down?*
C: *That's clear, go ahead and pull the speedlay down.*

Part of Attack 2 quickly leaves the building, and hauls extra hoses off of Engine 18. The group is known as Attack 4, so that they can be referenced separately from their original team. Attack 4 puts out the fire on the first floor, preventing a disastrous outcome to the incident.

This example is taken directly from T1. The danger was simulated: the props *cannot* burn down during training and instructors in charge of the simulation started the "spreading fire". In a similar real-life situation, the danger would be real and the students learned a valuable lesson from the training.

The situation described above exemplifies several aspects of firefighting. In the example, Command was able to redirect the company and save their lives because he had access to information they did not: from his vantage outside, he was able to see the fire on the first floor that was endangering everyone else. He would not have been able to affect change as quickly as he did if Attack 2's leader had not been listening to the radio communications. The leader of Attack 2 knew that he had firefighters free and realized that Command was not able to get anyone from the other group to assist, so he offered to help, a cross-boundary intervention [7] that inverts the command structure.

Information Flow

FERs rapidly make use of, modify, and relay information in real time. Information from the environment, personal knowledge, and the communications of teammates are recombined continuously while being translated into action. Information flow is critical: "*The worst thing on the fireground is when the communication goes bad...nothing else will screw you up like when the communication starts to drop*" [P6].

The information flow in firefighting teams builds upon face-to-face and shared radio communication. The necessities of firefighting and communication limitations

[2] The "*alpha side*", or "*A*" of a building is the side of the building facing the street; other sides are lettered counter-clockwise.

[3] A *speedlay* is a hose ready for rapid deployment [Cary Roccaforte (TEEX), personal communication].

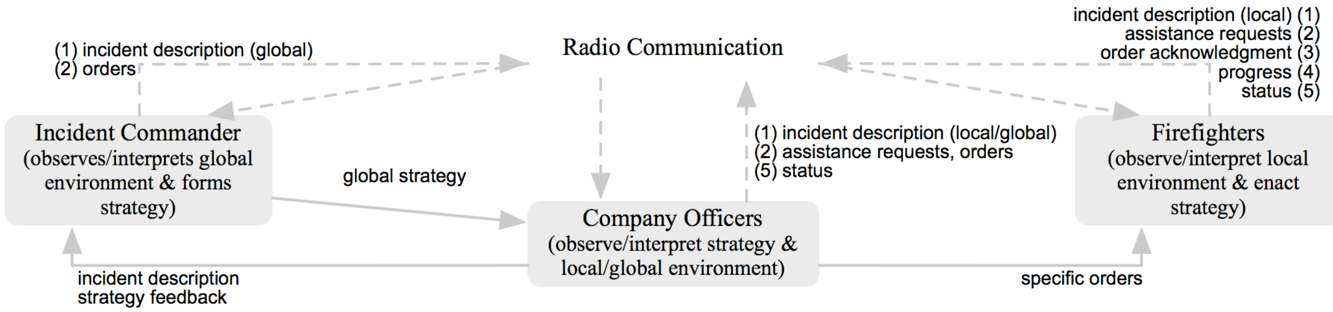

Figure 4. Information flows via communication in fire emergency response. Arrows indicate direction. Labels indicate the type of content. Radio communication is indicated with dashed lines, which have numbered labels corresponding to the list below.

give rise to the emergent behaviors of overhearing and ambient monitoring. These behaviors enhance team cognition, enabling implicit coordination.

Face-to-Face Communication

Face-to-face communication is preferred over all other types because it allows FERs to communicate quickly and clearly about goals and strategies: "*...it's better understood than over radio*" [P5]. Due to the embodied nature of human communication, face-to-face is less ambiguous than radio. In a collocated context, deictic references are clear and body language can play a significant role in communicating meaning. P5 explained that many face-to-face meetings are not broadcast over radio, allowing communication between only the individuals involved, and thus enabling the smaller group to avoid adding to the cognitive overhead of uninvolved parties and "*...tying up that channel which can be used for something else*" [P5]. This was also observed in practice by students.

Generally, the company officer relays a goal and a general strategy to the firefighters before they go into the building [P5]. Once inside, they can make small, situated changes to the strategy as they go, since the situations inside a building cannot be anticipated [P1, P3, P4, P5]. However, if the overall strategy is proving ineffective, and there is time, the firefighters will withdraw from the building to create a new plan [P5, P6]. [16]

Face-to-face communication is a requirement for deployed firefighters: company groups must make sure that they are within shouting distance and able to see one another [P5] [3]. This way, they cannot only speak with one another; they can also observe each other's conscious and unconscious body language, which they are able to interpret due to experience [P1, P3]. The students always stayed together, generally in groups of four, near their hoses, preventing individuals from getting lost or being unable to communicate.

Radio Communication

Radios are used primarily to share information among a deployed set of companies, rather than to relay strategy within a company. At each incident, a single radio channel is used by all involved [P2] [2, 19]. Due to the broadcast nature of radio, any time a transmission occurs all responders involved at the scene receive it. While the radio transmission channel reaches everyone, its bandwidth is limited, so its use must be optimized.

Many types of information are broadcast over the radio at an incident. According to interviewees and what we recorded during the training exercises, we discovered the following components of radio communication:

1. Transmission of specific information about the incident to other team members. If a firefighter notices that the structure inside a building is giving way, for example, this must go out to everyone at the scene, so that an evacuation can be called.
2. Orders for *ad hoc*, necessary activities or requests to perform them based on situated local information, such as ventilation or fire suppression in a certain area.
3. Acknowledgement of received orders and communications.
4. Progress updates on activities, including readiness. Members of company A might relay what rooms they have already checked for victims, so that company B knows where to go.
5. Personal status updates. For example, if a firefighter is injured, special assistance may be required to get out of the building. Such communication may be expanded to include the specification of the necessity for a RIT to assist, and the coordination of this process.

Sometimes radios fail; the backup system consists of human runners who are used to convey information to and from the fireground [P1, P4]. Radio communication failure can have many causes including an injured FER, one that is too busy to speak, or just a broken radio, which is why RITs are so important.

Feedback Loops

> *[FERs]...listen to command, they follow command, but they are also a thinking portion of the...team...you're going to give them guidance, they're going to start doing the work, and they're going to have feedback. And that's the thing that makes it work so well: that feedback and multiple sets of eyes* [P3].

Looking at the information flow within teams, there are several feedback loops (Figure 4). As FERs act at the fireground, they process their environment and interpret it, which is relayed to everyone else at the scene, forming a loop of information that is shared amongst the FERs.

The incident commander generates an overall strategy using personal knowledge and observation, as well as information from the other FERs. Overall strategy is relayed to the company officers, who interpret it with their observations, to generate a specific strategy for their company [P3]. This information is used by the firefighters to direct situated action, which affects what information they pass on to the other FERs. Thus, deployed firefighters pass information back to the incident commander, completing a larger loop.

These feedback loops are important, because they allow the emergency response process to be dynamic and situated. Through iterations of action, communication, and reaction, the FERs are able to quickly respond to changes in the environment, and officers are able to reorganize plans to suit the changes.

Emergent Practice

The limitations of information flow: the general unavailability of face-to-face communication and the limited bandwidth of the radio channel give rise to practices that help FERs to fill in the gaps in their knowledge about the situation. These practices, overhearing and ambient monitoring, aid in implicit coordination capabilities.

Overhearing

FERs overhear the radio communications at the fireground, which reveals to them what other members of their company and other companies are doing, granting a peek into the global situation and revealing opportunities to assist without explicit coordination [P6] [T1]. This ability is developed over time though experience [P5] and is similar to the coordination of workers in emergency call centers, where small groups of co-located call operators can tap into each other's phone calls in order to better assist one another [1]: coordination is almost automatic.

The training exercise described earlier demonstrates this effect clearly: Attack 2's officer realized that someone was needed to go downstairs to put out the fire, and offered part of his company to take care of it without being asked, facilitating the process of correcting the dangerous situation [T1]. Overhearing is a way of reconciling shared mental models and maintaining situational awareness without explicit coordination.

Ambient Monitoring

FERs maintain a mental model of the incident by listening to the background sounds in their environment and those coming through the radio from other FERs, in addition to immediate, local sensory perception [P1, P5, P6].

A specific example of this occurred during our observations: all firefighters rely on self-contained respirators while they are on the fireground and these have a low-air bell that sounds near the wearer's head. Each firefighter will be unable to breathe if the flow of air to his respirator runs out. Interestingly, because of its position, the bell is audible when the emergency responder uses his/her radio. During the observations, a team started to run out of air, the commander immediately became concerned about the air supplies of the other companies and made certain to monitor the others in the future [T1, T2, T3].

FERs sometimes ascertain one another's emotional and physical states from the sound of their voices: "*...you know when they're excited or when they're calm and when something's not right, you can tell just by their voice...you get to know them pretty...[well]*" [P1]. Utilization of voice tone cues enables participants to assemble a more complete sense of state. Ambient monitoring supports situational awareness by allowing the individual to gather environment information without communication, affording a glimpse into a global scope.

Distributed Cognition

FER teams have the advantage and disadvantage of being spatially distributed in and around the fireground. This distribution supplies more and varied information, but this information must be disseminated and integrated effectively. Team members act and observe the situation at various levels. For example, firefighters within the building have an extremely localized view: room by room; while the incident commander, a block from the scene, can see not only the burning structure, but also the areas around it and how those are being affected [P1] [T1].

> *…I had a crew inside fighting a fire, they went towards…the delta side of the house…back where the fire was, and did not realize that it was burning through on the bravo side, wrapping around and blocking them in.…I called them on the radio, let them know what was going on and they were able to back out and get out safely and knock down the fire.…you had to change your strategy a little bit, the first team through was not aware of what was happening to them.* [P3]

Team Cognition / Implicit Coordination

Interviewees indicated that they have a strong understanding of what their teammates are doing during firefighting operations, as well as the objectives of the team and individuals, indicating strong shared mental model building and situational awareness skills. They also subjectively described themselves as having a high anticipation ratio. Emergent practices develop this capability. These practices allow FERs to quickly determine what actions are needed, based on situational awareness and shared mental models, without the need for explicit communication [6].

Implicit coordination has two advantages over explicit coordination: first, it allows FERs to work quickly and safely in situations where timing is critical, eliminating the time associated with extra communication [12]. Second, micromanagement of the incident is unnecessary, freeing the incident commander to coordinate the incident at a high level of abstraction [P5]. Here we discuss components of fire emergency response work practice that allow firefighting teams to coordinate implicitly: shared mental models and autonomous operation.

Shared Mental Models and Situational Awareness

Shared mental models are a means for individual team members to "track" what other team members are doing, eliminating the need for some communication and boosting individual situational awareness [5, 6, 12]. FERs extensively use shared mental models in the field. Cross-training establishes the groundwork for shared mental model formation. Each emergency responder knows how to perform different roles, which supports her/him in understanding the concurrent experiences and needs of other team members. Further, because they live and work together for as much as a third of their lives [P1], they are able to build strong personal understandings of one another. These understandings lead to an ability to model one another's thinking processes in the field, strengthening their ability to implicitly coordinate [P1].

Shared mental models allow teams to streamline their operations [6]. For example, if company A must wait for company B to ventilate a portion of the roof, members of company A have a good idea of how long this will take. Their knowledge of how to perform that job themselves gives them an understanding of what is occurring with company B. This lessens the amount of explicit communication that must take place to keep the teams coordinated: "*You get to working with the same crew over time...it's a well-oiled machine, not much has to be said, everybody knows what's going on...*" [P3].

Autonomous Operation

> *You know [and] they know there's certain things that they have to do each time, and they're going to carry out those particular things no matter what....[I]f they see something different or something that may not work they're gonna speak up, they're not just going to sit there and...only do what they're told* [P3].

FERs know their job and their role at an incident. Based upon the situation, team structure, and experience, they know what needs to be done to accomplish the goals of the group when they arrive [P2, P3]. This allows them to operate autonomously using their own skills and judgment. The definition of roles within the team and information flows makes autonomous operation possible and allows for informal, *ad hoc* changes. For example, the first-arriving company knows that they need to gather information about the fireground and relay that information to later arriving units and that their company officer will become the standing incident commander [3, 11]. Generally, the incident commander needs only to modify operations from the routine [P2].

Cross-training and high levels of experience also allow for the informal process of *cross-boundary intervention* [7]. Such intervention can invert the command structure, allowing lower-ranking officers to utilize situated action to override plans when necessary [16]. An example of this occurred in our earlier example, when Attack 2 noticed that there was a need for assistance and spoke up.

DISCUSSION

Based on our ethnography, we extract salient components of fire emergency response practice that are important for new FERs to learn. FER students need experience with these components of practice in order to function within FER teams during incidents. We follow this distillation with a discussion of design implications, which embody the components' principles.

Components of Fire Emergency Response Practice

Teaching systems should enable students to develop essential skills they will need when firefighting. Information differential and uncertainty are inherent properties of FER work experience. Overhearing and ambient audio clues are emergent practices of implicit coordination. FERs must develop strategies to cope with the former, while the latter pair must be integrated.

Information Differential across Team Members

Information differential arises when members of a team directly acquire different pieces of information from the environment through distributed experiences across locations. This is an important component of systems supporting the education of FERs, because firefighting teams take different positions around a fire. Information differential functions as benefit and hindrance. Team members have access to different parts of the whole information picture. This allows the team as a whole to perceive and know more. Yet communicating and understanding this information can be challenging. Each member affects team performance through distributed situated interaction and problem solving from a different perspective. Information differentials must be integrated through skillful and careful communication to effect situated information flows like those in Figure 4; skills to perform as such are developed through practice. The application of these skills supports the team in developing emergent sensemaking.

Information is acquired in firefighting from three types of sources: immediate emic, externally perceived emic, and etic [13]. *Emic* information is derived through the experience of participation, while *etic* comes from outside sources [13]. Systems for teaching firefighters should supply different team members with these different types of information, and each different type should be useful to every team member's local situation.

Immediate emic information is local directly perceived sensory information. It is the information that FERs inside the structure access through physical experience. Much of this information is acquired on a room-by-room basis. Features include levels of visibility and smoke, ambient heat, heat from particular sources, cries of victims, etc.

Externally perceived emic information is also sensory, but perceived from outside the structure, sometimes from far away. Generally, a company officer outside commanding her/his company has information of this sort, as does the incident commander. While the information is localized to the fireground, it provides an overview of the situation. Externally perceived emic information allows reasoning about the "big picture": whether the building is on the verge of collapse, who has gone in or out, etc.

Finally, *etic information* comes from sources outside the team, such as information artifacts (floor plans, pre-planned strategies, etc.) or other agencies [T1, T2]. It is generally accessible to an incident commander, often in conjunction with emic information.

Individual Information Uncertainty

Communication faults, incorrect mental models, false information, and changes over time lead to information uncertainty, that is, questions about whether or not the information known by a team member is true.

Command: *Uhh…what teams are in the building still?*
???: *static*
C: *Attack 1, what is your location currently?*
Attack 1: *Uhh…alpha corner, first floor.*
C: *On the 1st or 2nd floor?*
A1: *Uhh…first floor.* [T1]

In the sample above, two problems arise: the Commander has lost track of who is in the building, prompting him to ask, and a radio fails, closing down the channel through which new information would normally be supplied. The situation calls for a change of plans and communication repair behaviors. Attack 1's position has become out-of-synch with where the Commander believes them to be, and he must ask for confirmation.

Because channels and information may be unreliable, information uncertainty is a reality of fire emergency response work. Mitigating uncertainty, through careful use of communication channels, observation, and mental models, is thus an important skill for firefighters, especially those in command roles.

Overhearing

Overhearing is the skill of listening in on shared communications, even when the communications are directed at others. Overhearing on a shared communication channel allows emergency responders to maintain mental models of what others are doing at the fireground implicitly and grants glimpses of the global situation, improving situational awareness.

Ambient Audio Clues

FERs rely on ambient sounds to supply them with information about their situation, the status of other team-members, and the incident overall. These sounds can come from two sources: the local environment, along with all other sensory information, and through radio contact.

Two concrete examples of clues are the popping sound of building timbers under stress [P1] and the loud ringing from the respirator system, indicating a low air supply [T1, T2, T3]. Both examples supply important clues for the FER directly experiencing them, in addition to aiding the entire team, if that responder uses the radio.

Design Implications

To support the education of FERs, we suggest the design of interactive systems that simulate essential components of firefighting work and practice. Design implications are derived from analysis of how FERs acquire information from their environments, and how information flows between them through communication in practice.

Require the mixing of situated face-to-face and remote shared audio channel communication modalities. Teams should work in situations in which members spend some periods collocated and others mutually remote. Participating in making decisions about which channel to use is critical for learning how to deal with information flows in stressful situations. Participants should be able to communicate with one another meaningfully both locally and remotely, and the shared channel enforces the need for learning and practicing implicit coordination and overhearing.

Create information differential with uncertainty. Participants should have access to distributed and thus diverse, situated information perspectives. Different members of the team should have different pieces of the information picture, but all of the information should be related to, but not necessarily relevant to completing, the current task, requiring team members to share and integrate information and enabling the formation of team cognition constructs. Due to the design of FER teams, some team members should be able to access various immediate emic information, while others should have access to externally perceived emic and etic information. Furthermore, if distributed remote team members *each* have information that is useful to others, then this requires effective use of the shared audio channel, including the development of skills such as overhearing.

Based upon FER work practice and our taxonomy, we suggest enabling information acquisition by team members in the following ways:

1. Actors in field roles (such as firefighters) should have access only to immediate emic information: local information about the situation acquired from the environment, which may have implications for the global situation.
2. Actors in coordinating roles (such as commanders) should access some mix of externally perceived emic information and etic information: global perspectives of the situation combined with information artifacts and other outside sources.

Distributing the information acquisition source types mirrors the way information is acquired in real life. It requires students to share information with each other carefully, so that personal and team information needs are met without unduly taxing the communication system and the cognitive processing of individuals.

Information should also sometimes go out-of-synch or be incorrect, so that team members must deal with uncertainty. This requires the use of shared mental models to resolve discrepancies and maintain situational awareness with correct understanding [5]. Information uncertainty is a reality of fire emergency response, as working perspectives sometimes come into conflict. Practicing coping will improve implicit coordination and overhearing.

Utilize audible clues that enhance situational awareness. Audible clues should supply information about the local situation with implications for the global situation, rewarding gathering immediate emic information. These clues should be able to be made available to other team members through a shared audio system, so that team members who are not collocated with the direct perceiver can gain utility from them when the shared audio is in use. The supply of ambient audio clues enables information gathering through the audio channel, and is directly tied to learning the skill of overhearing.

CONCLUSION

Fire emergency responders operate with time constraints on the information they acquire, process, and share, with life or death demands on performance. Communication and coordination are keys to effectiveness. Through implicit coordination, team members make better use of cognitive resources. Implicit coordination has previously been learned through firefighting experiences of burn training and actual incident response.

We propose the use of interactive simulations for teaching FERs. We have discovered components of FER practice that reward participants for implicit coordination. Thus, our ethnographic investigation of fire emergency response derives design implications based on practices of information acquisition and communication. In order to prepare FERs for the distributed cognition challenges they will face in the field, simulations need to mix communication modalities, create information differential and uncertainty, and utilize audible clues that enhance situational awareness. Implicit coordination is an essential component of team cognition for responding to an environment with these characteristics. Building such educational simulations will help FERs learn the implicit coordination skills that they need to save lives.

ACKNOWLEDGMENTS

Special thanks to the participants in our studies for their cooperation and to Cary Roccaforte and Mike Wisby for coordinating the interviews and our time at ESTI. Thanks to Sashikanth Damaraju for assisting transcribing video. This research was partially funded by the HARC Summer Scholars Program. All images taken with permission of ESTI.

REFERENCES

1. Artman, H., Waern, Y. Distributed cognition in an emergency co-ordination center. *Cognition, Technology, & Work 1*, 4 (1999), 237-246.
2. Carlson, G. P., Ed. *Incident Command System, 1st ed.* Fire Protection Pub., 1983.
3. College Station Fire Dept. *CSFD Departmental Standard Operating Procedures*. College Station, TX, Nov 2002.
4. Dugdale, J., Pallamin, N., Pavard, B. An assessment of a mixed reality environment: Toward an ethnomethodological approach. *Simul. Gaming 37*, 2 (2006), 226-244.
5. Endsley, M. R. Toward a theory of situation awareness in dynamic systems. *Human Factors 37*, 1 (1995), 32-64.
6. Entin, E. E., Serfaty, D. Adaptive team coordination. *Human Factors 41*, 2 (Jun 1999), 312–325.
7. Faraj, S., Xiao, Y. Coordination in fast-response organizations. *Management Science 52*, 8 (Aug 2006), 1155-1169.
8. Hollan, J., Hutchins, E., and Kirsh, D. Distributed cognition: toward a new foundation for human-computer interaction research. *ACM Trans. CHI 7*, 2 (2000), 174-196.
9. Jiang, X., Chen, N. Y., Hong, J. I., Wang, K., Takayama, L., Landay, J. A. Siren: Context-aware computing for firefighting. *Pervasive Comp. 3001* (2004), 87-105.
10. Jiang, X., Hong, J. I., Takayama, L. A., Landay, J. A. Ubiquitous computing for firefighters: Field studies and prototypes of large displays for incident command. *Proc. CHI 2004*, ACM, 679-686.
11. Landgren, J. Making action visible in time-critical work. *Proc. CHI 2006*, ACM, 201-210.
12. MacMillan, J., Entin, E. E., Serfaty, D., Communication overhead: The hidden cost of team cognition, Ch. [14], 61-82.
13. Pike, K. L., *Language in relation to a unified theory of structure of human behavior,* 2nd ed. The Hague: Mouton. 1967.
14. Salas, E., and Fiore, S. M., Eds. *Team cognition understanding the factors that drive process and performance*, 1st ed. APA, 2004.
15. Serfaty, D. E., Entin, E. E., Volpe, C. Adaptation to stress in team decision-making and coordination. In *Proc. Human Factors and Ergonomics Society* (1993), 37, 1228-1233.
16. Suchman, L. A. *Plans and situated actions*. Cambridge Univ. Press, 1987.
17. Technical Committee on Fire and Emergency Service Organization and Deployment. *NFPA 1710 Standard for the Organization and Deployment of Fire Suppression Ops., Emergency Medical Ops., and Special Ops. to the Public by Career Fire Depts.*, 2001 ed. National Fire Protection Assoc.
18. Texas Engineering Extension Service. *TEEX Fire Field*. Sep. 14, 2006. Online: http://www.teex.com/teex.cfm?pageid=ESTIprog&area=ESTI&templateid=1527.
19. Wieder, M. A., Smith, C. M., Brakhage, C. S., Eds. *Fire Service Orientation Terminology, 3rd ed*. Fire Protection Pub., Oklahoma State Univ, Stillwater, OK, USA, 1993.