Constructing Common Information Spaces across Distributed Emergency Medical Teams

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ABSTRACT

This paper investigates coordination and real-time information sharing across four emergency medical teams in a high-risk and distributed setting as they provide care to critically injured patients within the first hour after injury. Through multiple field studies we explored how common understanding of critical patient data is established across these heterogeneous teams and what coordination mechanisms are being used to support information sharing and interpretation. To interpret the data, we drew on the concept of Common Information Spaces (CIS). Our results showed that teams faced many challenges in achieving efficient information sharing and coordination, including difficulties in locating and assembling team members, communicating and interpreting information from the field, and reconciling differences in team perspectives and information needs, all while having minimal technology support. We reflect on these challenges to suggest an extension of the classic CSCW time-space matrix, as well as future development of CIS as an analytical framework. The paper concludes with design opportunities for supporting highly distributed and heterogeneous teamwork in time-critical work environments.

Author Keywords

Common information spaces; teamwork; coordination mechanisms; information sharing; information handover; pre-hospital patient care; emergency medicine; healthcare.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Effective communication and coordination are essential for efficient patient care in high-risk, time-critical medical settings, such as trauma resuscitation [13]. During resuscitation, an interdisciplinary, ad hoc trauma team rapidly identifies and treats life-threatening injuries following an established protocol. The goal is to stabilize critically injured patients and develop a plan for definitive care. Timely and accurate sharing and interpretation of information collected in the field and en route to the hospital—*pre-hospital communication*—is a critical first step towards achieving this goal. Despite its critical role, communication between care providers in the field and those in the hospital remains inefficient, requiring further study [25,29,31,44]. Prior work has focused on developing solutions to better support field data collection and transfer from the field to receiving care centers [11,29,45]. Even so, there is a lack of in-depth, empirical understanding of the information flow across teams participating in this process, and how they coordinate work and communicate to share and make sense of the patient information.

To bridge this knowledge gap, we investigate coordination and real-time information sharing as the pre-hospital information flows across four emergency medical teams—from emergency medical services (EMS) teams in the field to teams in the emergency communication centers, to teams in the emergency departments, and to trauma teams at the point of care. In particular, we ask how is common understanding of the pre-hospital information established across these teams, what coordination mechanisms are used, and what challenges exist and how to address them to support seamless information sharing and interpretation.

To answer these questions, we conducted multiple field studies in an urban teaching hospital and trauma center, and drew on the concept of Common Information Spaces (CIS) [9,33]. CIS was introduced as a CSCW framework for analyzing the use of shared information in cooperative work, e.g., how is information presented to actors and how the actors interpret the information. Central to this framework are the processes that enable cooperative work through common understanding of the shared information. Pre-hospital communication is a cooperative process that requires common understanding of the shared information among all participants. The CIS framework was, therefore, suitable for our study because it allowed us to systematically analyze how common understanding and coordination are achieved in this complex teamwork. Compared to previously analyzed CISs [7,9,26,30], the case of pre-hospital communication is characterized by high-risk, oscillating collaboration: periods with actors going about their ordinary work rapidly change into boosts of

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highly critical episodes of interaction. As such, our study allowed us to innovate around the CIS concept itself by adding new parameters to better characterize distributed and heterogeneous cooperative work that is highly dynamic and episodic. Our study also highlighted the challenges in interpretation work due to actors' diverse backgrounds and experiences, as well as diverse contexts in which their work unfolds. To make this central role of interpretation work more visible in studying collaboration, we modified the classic time-space matrix [19] by adding *work practices* as a new dimension. In short, we contribute to CSCW by:

- Providing new insights into how CIS is achieved in a distributed, high-risk, and oscillating work setting;
- Extending the concept of CIS by adding two new parameters: the scalability of collaboration and the multiplicity of information spaces;
- Modifying the classic CSCW time-space matrix by adding work practices as a new dimension;
- Discussing design opportunities for supporting highly distributed and heterogeneous teamwork in time-critical work environments.

THE CONCEPT OF COMMON INFORMATION SPACES

CSCW researchers have been defining and developing the concept of CIS for more than two decades. Schmidt and Bannon [33] first proposed it as a conceptual framework for CSCW. To date, various studies have used the CIS concept to examine how understanding of shared information or objects is constructed in particular settings. Below we outline its evolution and refinements.

Schmidt and Bannon [33] introduced CIS as a part of cooperative ensembles, where actors coordinate and communicate by adjusting their work, thereby contributing to the overall work arrangement. Because actors are semi-autonomous and often physically distributed without an agent to control and command their actions, a central challenge was found in the articulation work, i.e., in coordinating and aligning distributed tasks across time and space. Schmidt and Bannon argued that this challenge could be addressed through CIS, which consists of the information that is put in common and the interpretation work that goes into constructing at least temporarily shared meaning of that information. In collocated work settings, constructing CIS is supported by physical proximity, which allows for overhearing and quick query-response interactions, as illustrated in several workspace studies [6,18,23]. Distributed CISs, however, lack such support.

Reddy et al. [28] refined the collocated-distributed perspective after observing the use of an electronic patient record in an intensive care unit. They found that work practices were so diverse that many advantages afforded by physical proximity were lost; the assumption that collocation is advantageous in constructing CIS only holds true if collaborators can establish common understanding of each other's work. We have similarly found that physical proximity was most useful for teams with a shared set of information needs, like the team in the emergency communication center, whereas interdisciplinary trauma teams benefited from collocation only after establishing the shared understanding of the patient status.

Bertelsen and Bodker's studies of "massively distributed" spaces such as wastewater treatment plants [7] challenged the idea that common information spaces are about "everywhere, everything access" from one single place (e.g., a shared database) by showing how workers controlled the plant as they moved about, meeting centrally only at coffee breaks to exchange information. The concepts of mobility, peripheral awareness and at-a-glance overview took new meanings as more studies contrasted collocated and distributed cooperation practices [14,30,35]. Fields and colleagues further expanded the notion of CIS by focusing on heterogeneous spaces such as the airport [14,35]. Their studies of coordination in the control tower and other airport sites showed that geographical and organizational regions of a large work site are changing and contingent, and can be regarded as a constellation of overlapping, interdependent CISs that are articulated through boundary objects. To succeed in supporting cooperation at this scale, technology interventions must be capable of crossing these boundaries, as well as allowing for any locally produced interpretations to be held in common. Similar to these findings, our study showed that the pre-hospital CIS consists of several interdependent and overlapping CISs. These information spaces, however, pose significant challenges to work articulation because there are fewer adequate boundary objects in use.

Hospital wards are another example of distributed and heterogeneous CISs in terms of space, workers, and artifacts [9,26,41]. Using the insights from discussing several CISs, including the hospital ward, Bossen [9] proposed a framework consisting of seven parameters that, when combined, characterize a particular CIS: 1) *the degree of distribution*: the degree to which people are physically distributed; 2) *the multiplicity of webs of significance*: the differences in cultures, languages, experiences and expertise; 3) *the level of articulation work required* to achieve coordination; 4) *multiplicity and intensity of means of communication*: the number of available means of communication to support coordination work; 5) *the web of artifacts*: the number and type of available coordination mechanisms, such as plans, schedules and checklists; 6) *immaterial mechanisms of interaction*, such as habits, divisions of labor, and organizational structures; and 7) *the need for precision and promptness of interpretation*.

Examined together, these prior studies of different CISs have produced rich accounts of how common understanding and coordination are achieved in person or virtually through artifacts. The high-risk, oscillating collaboration of the pre-hospital communication case complements analyses of prior CIS cases. For example, the wastewater plant space was also distributed, but work pace

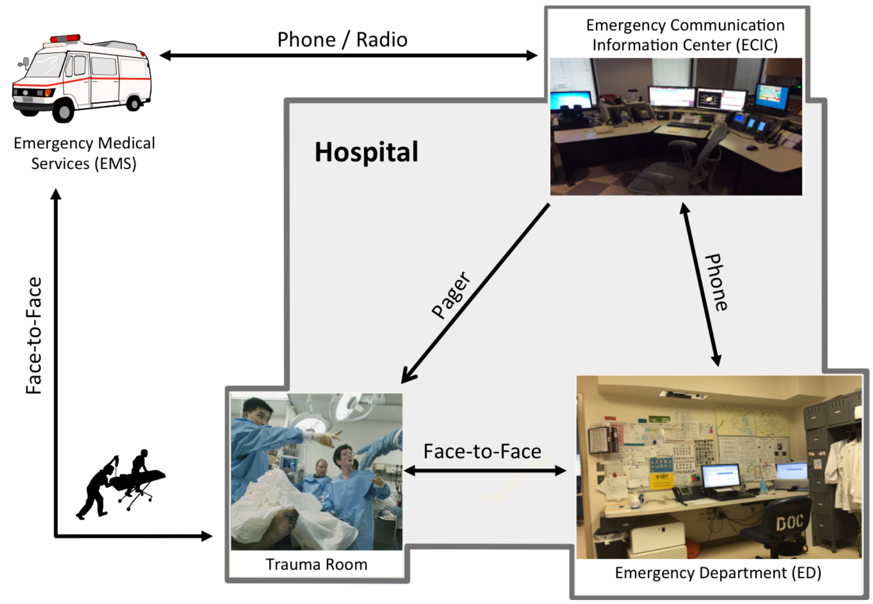

Figure 1: The pre-hospital communication process.

was slower and less intensive [7]. The hospital wards were distributed too and split into several regions, but work pace was less critical than in the pre-hospital case [9]. The pre-hospital and the oil-well planning CISs share the episodic assemblage of technologies and actors for providing emergency care and informational planning, respectively. However, in the oil-well planning case, there was more time to prepare and plan ahead, and fewer demands to act immediately on highly critical issues [30]. Our work investigates a CIS that exhibits a novel combination of high-risk, time-critical activity with oscillating temporal rhythms. We also extend the CIS framework by identifying two new parameters—the scalability of collaboration and the multiplicity of information spaces. These new parameters are important to consider when studying cooperative work that occurs in stages and involves distributed, heterogeneous teams.

THE PRE-HOSPITAL COMMUNICATION PROCESS

The pre-hospital communication process usually involves four teams from different disciplines (Figure 1). The *Emergency Medical Services (EMS)* team provides initial medical care in the field and transports patients to the nearest point of definitive care. The *Emergency Communication and Information Center (ECIC)* is a hospital facility with a team of communication specialists. The center is the first point of contact for anyone sending patients to the hospital. The ECIC team coordinates patient transport to or from the hospital, dispatches ground and air medic teams, answers phone or radio calls, coordinates arrivals for critically injured patients, and activates trauma teams. The *Emergency Department (ED)* team provides a full range of emergency diagnostic and treatment services for acutely ill and injured patients. During each shift, one physician is responsible for supervising the entire ED work and answering calls from the ECIC and other facilities. The *trauma team* is a hospital-based team, consisting of a leader (senior surgical resident, fellow or attending), an ED physician, a junior resident, an anesthesiologist, a respiratory therapist, bedside nurses, and a scribe. Trauma teams are hierarchical, with each team member having a pre-defined role and responsibilities: the leader supervises care and makes decisions; a junior resident performs hands-on patient evaluation; bedside nurses provide bedside care, while the scribe documents the process.

Typically, patient information collected by EMS in the field is first relayed to the ECIC team. This initial exchange occurs en route via radio or cellular link, as the EMS team transports the patient to the hospital. Upon receiving this report, the ECIC team relays the information to an ED physician, and determines the activation level for trauma team. Trauma centers have three levels of team activation based on the severity of patient injury: patient transfer, trauma stat (low acuity patient), and trauma attending (high acuity patient). Patient information is then summarized into a brief message and sent to the trauma team using pagers. Upon being notified, members rapidly gather in the resuscitation room. As they assemble, an ED physician relays known patient information. The trauma team uses this information to prepare equipment and summon any additional specialists. Patient handoff occurs in the room between the EMS and trauma teams. A member of the EMS team gives a verbal report, summarizing patient injures and en route treatments. Once the patient is transferred to the room stretcher, the team starts assessing the patient. The resuscitation process usually lasts about 20 minutes.

METHODS

Because the pre-hospital CIS involves four teams, we conducted multiple field studies, each time focusing on a different team and their work practices. We next describe our approaches to understanding this CIS in greater detail.

Research Settings

Our study took place in an urban pediatric teaching hospital with a Level I trauma center. We performed fieldwork in different hospital areas, including the ECIC control room, emergency department, and resuscitation rooms.

The ECIC control room, located at the top level of the hospital building, is a high technology facility, with three workstations equipped with a desktop computer and two monitors, a radio communication system and a landline phone. The ED and resuscitation rooms are located at the ground level. The main ED office is in the center of the ED, and is used by ED physicians on duty to answer calls and document patient information into electronic systems.

Nearby nurse stations and work spaces for other physicians allow for quick walk-ins and opportune conversations. Trauma patients are treated in two designated rooms within the emergency department. Both rooms are packed with medical instruments and equipment but lack IT systems for synthesizing patient data and supporting teamwork. Patient data are communicated verbally and recorded manually.

Data Collection

We collected data using ethnographic methods such as in-situ observation, interviews, video review, content analysis of artifacts, and audios of EMS calls. The hospital's Institutional Review Board (IRB) approved the study.

In-Situ Observation

We spent a total of 100 hours in the ECIC control room and 90 hours in the emergency department and resuscitation rooms to understand how the work of acquiring, documenting, sharing and interpreting pre-hospital information is accomplished by these teams, as well as how team members collaborate within and across team boundaries to prepare for patient arrival. On average, we spent eight hours a day in each setting, covering both day and night shifts, as well as shift handovers. Observations focused on different aspects of the work, including the artifacts, types of activities, types of information gathered and shared, and coordination within and across teams. We collected a variety of materials, including observational notes, transcripts of calls and conversations between team members, transcripts of pager notifications, and photos of the artifacts and the rooms. After each observation session, field notes were transcribed into an electronic observation log that included detailed descriptions and reflections of what was observed. We also had access to 68 audiotaped pre-hospital communications between EMS and ECIC teams. This dataset was used for additional analysis of communication between the two teams.

Semi-Structured and Contextual Interviews

We conducted formal, 30 minutes to 1 hour long semi-structured interviews with 16 trauma team members, including five emergency medicine physicians, eight surgical residents, one surgical fellow, one respiratory therapist and one nurse practitioner. The interviews focused on work responsibilities, educational background and experience, pre-hospital information needs, and concerns about the pre-hospital communication process.

Following the same protocol, we interviewed eight ECIC team members and six ED physicians. The interviews lasted 15-45 minutes, depending on their availability. We also conducted contextual interviews during observations to obtain details about the observed activities. All interviews were transcribed into the electronic observation log.

Video Review

To analyze patient handoffs between EMS and trauma teams, as well as information handovers between ED physicians and trauma team members, we reviewed videos of 32 actual trauma resuscitations. Video records were captured by two video cameras; one provided an overhead view and the other provided a side view of both the team and the resuscitation room. Video review supplemented our observations in the room.

Data Analysis

We used an open coding technique to analyze the data from observations and interviews. We first reviewed the electronic observation log and interview transcripts to get an overview of the context. In the subsequent stage, we transferred data into Atlas.ti, a program for organizing, storing, and manipulating qualitative data. Based on Bossen's elaboration of the CIS concept [9], we focused our analysis on work practices, communication behaviors, interactions, critical information needs, and types of tools and technologies used. After the second round of coding, we identified major themes describing how different teams coordinate with each other to achieve common understanding and accomplish work. This step was followed by identifying representative quotes and vignettes to support the claims. We also performed content analysis of the photographs taken during fieldwork. This analysis provided additional contextual information, complementing the analysis of interviews and observational notes. For example, a photograph of an ECIC team member's notepad helped us understand the types of information that were recorded and their spatial organization on the notepad.

In addition, we transcribed video recordings of actual resuscitations into an excel sheet, including the timestamps, speakers, dialogue, and actions. While reviewing the videos, we paid attention to conversations and interactions between ED physicians and trauma team members to better understand the process of information handover. As we progressed with the review, we began to identify common patterns in their verbal exchanges and types of information that were communicated. To better illustrate the observed patterns, we provide brief excerpts from transcripts that include descriptions of utterances and events.

THE PRE-HOSPITAL CIS

Using Bossen's elaboration of the CIS framework [9], we next describe the pre-hospital CIS. In doing so, we adopt the seven parameters but group them under three broader characteristics of our CIS—massive physical distribution, team heterogeneity, and coordination mechanisms—to create a coherent, rich account of how the shared understanding and coordination are achieved among distributed emergency medical teams (Table 1).

Massive Physical Distribution of the Pre-Hospital Work

To describe physical distribution of work and the challenges it creates in the pre-hospital CIS, we used three parameters from Bossen's framework [9]: the degree of distribution, multiplicity and intensity of means of communication, and the need for precision and promptness of interpretation. Spatially, all teams participating in the pre-hospital communication process function over a large physical area (Figure 1): EMS teams are en route to the

Bossen's Seven CIS Parameters →	Pre-Hospital CIS →	Pre-Hospital CIS Low-Level Characteristics
• Degree of Physical Distribution • Multiplicity and Intensity of Means of Communication • Need for Precision and Promptness of Interpretation	Massive Physical Distribution of Pre-Hospital Work	• Locating and Assembling Team Members • Communicating and Interpreting Information
• Multiplicity of Webs of Significance	Heterogeneous Emergency Medical Teams	• Discipline-Specific Terminology Use • Information Needs • Information Reliability
• Web of Artifacts • Immaterial Mechanisms of Interaction • Level of Required Articulation Work	Coordination Mechanisms in the Pre-Hospital CIS	• Artifacts as Material Coordination Mechanisms - Personal, Local, Common Artifacts • Immaterial Coordination Mechanisms - Division of labor, Overhearing • Oscillating Levels of Articulation Work

Table 1: Characteristics of the pre-hospital communication CIS: From Bossen's seven CIS parameters to three broad characteristics of the pre-hospital CIS to its low-level characteristics

hospital; the ECIC team is at the top level of the hospital building for an easy access to the helipad; ED physicians and charge nurses move around the emergency department on the ground floor; and, trauma team members go about their own duties in different hospital units, but convene for a trauma case in the resuscitation room. Work in the pre-hospital CIS is, therefore, distributed by necessity.

Although technology such as phones and radio support pre-hospital information sharing, the distributed nature of the pre-hospital CIS poses challenges to achieving seamless communication and coordination across teams. We describe two major challenges: locating and assembling team members, and communicating and interpreting information.

Locating and Assembling Team Members

Most distributed work spaces, including not only CISs like the wastewater plant [7] and hospital wards [9,26], but also settings such as the construction site [22] or design studio [5], provide overlapping zones in which actors can move around, relying on visual cues to maintain awareness of whereabouts of their colleagues. In contrast, locating and assembling actors in the pre-hospital CIS is challenging because their paths have fewer intersections.

For example, ED physicians may need to know the whereabouts of trauma team members. Although most team members assemble in the resuscitation room shortly after being notified, we observed several cases with critical team members missing or arriving late. In one case, for instance, the anesthesiologist was not present when the patient arrived, so the physician delegated airway management to the nurse. Meanwhile, the physician called the ECIC team, requesting another pager notification for anesthesia; the follow-up message stated: "Update-Anesthesia Needed-1 Trauma Stat in ER." Similarly, ED physicians and trauma team leaders may decide to call for a specialist (e.g., neuro or orthopedic surgeon) based on the patient's status. As we observed, estimating the specialists' arrival time to the resuscitation room was difficult, often requiring prompts and follow-up calls to check if the specialists were coming.

The ECIC team needs to know location of the EMS team to estimate patient arrival time so that trauma teams can be assembled in time for the patient. Normally, the EMS team would communicate their estimated time of arrival (ETA) in their initial call to the ECIC. However, we observed instances in which EMS teams neither specified the ETA nor reported their location. In addition, the reported ETA was not always accurate. We observed one patient arriving to the resuscitation room approximately two minutes after the overhead announcement, even though the announcement stated that the patient would arrive in 14 minutes. Because the notice was short and inaccurate, only two nurses arrived to the room before the patient; the EMS team then waited for other trauma team members to assemble before starting their verbal report. In another case, the ETA was specified as four minutes, but the entire trauma team waited for more than 15 minutes. Despite their need for awareness of the whereabouts of other actors, hospital teams lack the mechanisms for tracking patients and medical personnel in this CIS.

Communicating and Interpreting Information

Similar to other dynamic and safety-critical CISs, all actors involved in the pre-hospital CIS need a precise and prompt interpretation of the patient information. The distributed nature of the CIS and the use of traditional telecommunication channels make this requirement challenging. For example, radio signal is often unstable and fails to work in many areas. Both ED and ECIC teams complained about poor reception during EMS calls. These complaints were also confirmed through our observations of specific requests to clarify and repeat portions of their reports. An ED physician commented:

> *"Sometimes you cannot really hear what they are saying, the communication system is not great. So we end up*

making assumptions and guesses, based on a little bit of information we have." [ED#3]

Communicating context in which the information was generated was also challenging because the visual aspects of communication were blocked. Solutions have been offered to address this challenge for some CISs, including a video channel for the airport setting [14] or an indication of the information originator in hospitals [3,9,42]. Teams in the pre-hospital CIS mostly use analog channels to share patient data, limiting the amount of contextual information that can be communicated. An ED physician explained: "*Sometimes it is difficult to get information, because it is 'piecemeal,' meaning I get some snippets, but I don't get the full history*" [ED#5]. To augment the EMS reports, hospital teams expressed the need for visuals from the incident scene to better anticipate the severity of the patient's injury. Some EMS providers have started taking photos of the incidents using their personal phones as a workaround. A surgical resident described:

> "*A lot of times, whoever brings [the patient] in, will bring a picture of the car, and that's useful. […] If they were in a car crash going 20 miles an hour, and they were a restrained driver, and then in the picture of the car, the whole driver's side is just completely torn apart, so you can see where the force came from.*" [TT#6]

We next describe how the heterogeneity of teams affects information sharing and work coordination in the pre-hospital CIS. This CIS characteristic is equivalent to the "multiplicity of webs of significance" parameter [9].

Heterogeneous Emergency Medical Teams

The more heterogeneous the teams participating in a CIS are—that is, the more diverse cultures, languages, and professions are present in and across teams—the more work is required to put information in common and to achieve common understanding [9]. Because actors in a CIS may form different perspectives, even for identical information [28,33], there is a need to balance those perspectives.

The pre-hospital CIS involves multiple heterogeneous teams performing different aspects of medical work, and thus, having different levels of medical background. For example, members of EMS teams are trained at the EMT-C (Emergency Medical Technician-Comprehensive) level so they can take care of patients, while members of the ECIC team need training at the EMT-B (Emergency Medical Technician-Basic) level only. In contrast, ED physicians and trauma team members have their own specialties, and various medical and training backgrounds. These differences have an impact on inter-team communication, including terminology use and interpretation, information needs, and information reliability.

Terminology Use and Interpretation

Different educational backgrounds and training levels may lead to differences in the use and interpretation of medical terms. EMS and ED teams, for example, come from different disciplines and may not use the same terminology when discussing patients, as one ED physician explained:

> "*The word of lethargic for example. I have no idea what that means to them. I know what it means to me. To me, it means you have to try hard to get them [patient] to respond. But to [patient's] mom or [EMS] paramedics, it just means they are asleep.*" [ED#4]

Even so, considerable knowledge of different work processes and settings is important. Despite having the lowest level of technical training, the ECIC team members would often bridge the communication gap between the EMS and ED teams by "translating" EMS reports:

> "*I think we can help because we are familiar with how it works out there as paramedics, and how we work in here. So we can merge the two and we can help eliminate some of the confusion doctors have because they are in their own world and EMS people out there are in their own world, when these two come together, sometimes it can be confusing to each other.*" [ECIC#2]

Information Needs

Through interviews with members of different teams, we found many differences in information needs and priorities. The ECIC team needs details about patient injuries to determine the trauma team activation level. ED physicians and trauma team members need contextual information from the accident scene (e.g., photos) to better anticipate the patient's needs. We also observed differences in information needs among the members of the same team. The interdisciplinary nature of trauma teams, for example, means that different roles have different information needs: bedside nurses need information about en route treatments to decide about subsequent fluid administration, whereas respiratory therapist and anesthesiologist need information about the patient's airway status.

In addition, the level of detail about patient injury needed by different actors is not clearly established between pre-hospital and hospital teams, leading to some tension. The ECIC and ED teams may receive different information about an incoming patient during EMS calls. Depending on the available time and patient acuity, EMS reports can range from very brief to very long and detailed. For example, if the patient is arriving within a few minutes, the purpose of the EMS call is to quickly announce the patient's arrival and report only critical patient information. In contrast, if more time is available, EMS teams prefer giving comprehensive reports. It is common that EMS reports in such cases include some unnecessary detail, overwhelming the ECIC and ED teams and requiring additional articulation work:

> *"I want a short, sweet assessment of three criteria that I need. […] I don't need that 'live in the home' all that nuanced information. Give me what I need, and I don't know if EMS really knows what it is we are looking for.*

[…] As you may see, I am rolling my eyes over and over again, I am like just give me the information." [ED#3]

We observed similar challenges during patient handoffs in the resuscitation room. It sometimes took EMS team members several minutes to report the patient's medical history. Although detailed reports are valuable for creating a larger picture of the patient injury, they are often ignored by trauma team members whose priority is the immediate patient assessment, especially when treating acutely injured patients [32,43]. A bedside physician explained:

"I don't listen to the report. Because they talk too much. […] Like too much information, sometimes I feel like I have to ignore what they have just said to focus on my patient care." [TT#1]

Our analysis of videos confirmed this practice, as we frequently observed only ED physicians talking to EMS teams during patient handoffs, while other team members proceeded with the patient evaluation and treatments. For a more efficient patient handoff, the content and structure of EMS reports should tailor to the needs of trauma team members, as expressed by a surgical resident:

"If (EMS) can organize before coming in, that would be helpful. […] If I know they can do it within five seconds, then I can listen to them, and jump into my part." [TT#1]

Information Reliability

We heard both ECIC and ED team members commenting about the varying quality of EMS reports due to the different levels of EMS training. As we learned from interviews, some EMS teams performed better than others:

"*We don't know the level of training of individuals in reporting information. […] You are gonna get huge variability in their medical assessment skills. So I need to know is there a physiological change in the patient, is there an obvious fracture, and is there a mechanism. I don't always get those three things.*" [ED#3]

ED physicians expressed concerns about insufficient EMS training in responding to the needs of pediatric patients. Because EMS paramedics rarely complete pediatric training, their reports about pediatric patients are often incomplete or inaccurate. Another ED physician explained:

"*I don't trust 50% of what they say. They just don't have good experience with kids. So if you take a 2-year old child and put a collar on him, and stretch him down on the board, then he starts screaming. And according to paramedics, who don't understand children, they might say he is being irrational, he is having bad mental status. Or if you got a fractured bone or something, a very common pediatric response to pain is sleep. To paramedics, that means unconscious.*" [ED#4]

Coordination Mechanisms in the Pre-Hospital CIS

To describe how emergency medical teams coordinated work in the pre-hospital CIS, we combined three parameters from the Bossen's framework [9]: the web of artifacts, immaterial mechanisms of interaction, and the level of articulation work required to achieve coordination. Schmidt and Simone [34] first used the concept of coordination mechanisms to describe material artifacts. The was then extended by Bossen [9] to include immaterial mechanisms of interaction, such as organizational structures, schedules, and procedures. Following this distinction between material and immaterial coordination mechanisms, we next describe the material artifacts and immaterial coordination mechanisms that were used in the pre-hospital CIS.

Artifacts as Material Coordination Mechanisms

We observed teams creating and using three types of artifacts to facilitate information sharing, interpretation and documentation: personal, local, and common artifacts.

Personal Artifacts. Personal artifacts support individual work and thought processes [41]. They were rarely shown to others on the team or shared across different teams. Team members from all teams created and used personal artifacts for various purposes, including recording, organizing, and recalling information. The most commonly observed personal artifact was paper. When talking to EMS teams, the ECIC team members first jotted down notes about the patient on their personal notepads. These hand-written notes served as a memory aid, containing abbreviations for patient information. We also observed the use of visual attributes, such as text orientation, spatial clustering, arrows and symbols for re-arranging the location of notes. This visual and spatial organization of notes helped the ECIC team members reconstruct the patient's story as they were relaying it to the ED physician and later entering it into the electronic systems. Having their notes at hand was also useful when responding to questions, as explained by an ECIC team member:

"*I'd like to be able to see certain information right away rather than having to click through several layers of screens. Someone [ED physician] may call back asking what is the blood sugar, I don't have to be like 'crap, what is it.' I can just take a look at my notes.*" [ECIC#5]

ED physicians found sheets of paper more convenient because they were always on the move. The neatly folded sheet was used to document information about all ED patients, including those with traumatic injuries. Physicians would visually separate patients by drawing a line or by numbering each patient case. Notes were also occasionally used when relaying information to trauma teams. Some ED physicians, however, chose to skip note taking and instead relied on memory to record the information about incoming trauma patients and then recall it during the briefing with trauma teams: "*I don't use paper. I know some people do. I just remember it*" [ED#3]. Remembering the details was sometimes challenging so ED physicians remembered only key or abnormal information, as we heard in an interview:

> "*I usually will record them in my head as normal or abnormal. So something is abnormal, I will say pulse is 140, blood pressure is 70/30, you know, the team does not need to know the exact number, they just need to know if it's normal or abnormal.*" [ED#5]

EMS team members also used paper to record information in the field and then referred to their notes during patient handoffs in the resuscitation room, especially when reporting historic or transitory information, such as patient vital signs and medication doses. In contrast, trauma team members were rarely seen using personal artifacts. Sometimes, however, team leaders would use a medical record or a paper artifact for note taking. For example, team leaders at our site use a checklist to ensure compliance with the resuscitation protocol. We observed that leaders often used the checklist to jot down pre-hospital information about incoming patients in the margins as ED physicians or EMS teams were relaying the information.

Local Artifacts. Local artifacts are used by a team operating within a bounded space. In our study, both ECIC and trauma teams worked within the bounded spaces of the ECIC control room and resuscitation room, respectively.

The ECIC room is equipped with both state-of-the-art technology and traditional low-tech artifacts for coordinating work. For example, four large monitors mounted on the wall provide live video feeds from the cameras installed at the helipad, at the entrance to the ED, in the main resuscitation room, and in the ED hallway. The ECIC team members could see when EMS teams arrived to the hospital, either by ground or by air, and take actions, if needed. They also used monitors to track down ED physicians when they had difficulties reaching them via phone. Additional local artifacts included paper-based tools such as the sheet with who-is-on-call information for all teams involved in the process. This paper artifact was used to determine the recipients of the pager notifications or for forming patient transport teams.

The resuscitation room, on the other hand, has limited technology support for coordinating work. We rarely observed ED physicians or trauma team members using technology support for presenting pre-hospital information. Occasionally, though, we observed ED physicians glancing at a whiteboard next to the room entrance to maintain awareness of who is present in the room; the whiteboard allows trauma team members to "check in" by writing their names and arrival times using their designated roles. This lack of technology support presented a unique challenge in sharing information in the room: ED physicians often spent unnecessary time and effort in repeating the pre-hospital information as team members were assembling and inquiring about the incoming patient. In one case, we observed the physician repeating the pre-hospital information seven times to seven different people, including the scribe nurse and surgical resident who arrived late. Although repeating information was time consuming and caused interruptions, it also ensured that all members had received critical information, which was simultaneously repeated to the already present team members.

Common Artifacts. Common artifacts are used across different teams. This type of artifact is considered a boundary object [38], containing "packaged" information that can be transferred from one team to another to support information interpretation. For example, a desktop computer system FirstNet is an emergency information system for managing patients admitted to the emergency department. Both ECIC and ED teams have access to this system and use it for the initial charting of incoming patients. After relaying information to the ED physician, ECIC team members would enter information from their notepads into the FirstNet system. Despite the shared view and access, we observed that ED physicians rarely used it to obtain additional information about their patients. Instead, they walked over to the resuscitation room. Another example of a common artifact is the paging system, which is designed for composing and sending a brief message about the incoming patient to specific people or a target group (e.g., trauma team). However, the pager messages are short, up to 160 characters, limiting the ability to communicate detailed and contextual information.

Immaterial Coordination Mechanisms

Immaterial coordination mechanisms include habits, division of labor, routines, procedures, peripheral awareness, and knowledge about a worker's background or experience [9]. In our study, we observed members of different teams leveraging several immaterial coordination mechanisms, including division of labor and overhearing to complete complex tasks.

Division of Labor. Division of labor based on roles, functions and professions is a prevalent coordination mechanism, allowing individuals and groups to focus on their tasks using particular skills and expertise [40]. Healthcare services, including hospitals, are extensively using this coordination mechanism.

The pre-hospital care setting is no different. Both ED and trauma teams have clearly defined divisions of labor. Upon being notified, ED physicians and nurses proceeded with work according to their roles: the charge nurse activated the scribe and medication nurses, and announced patient arrival using the overhead announcement system; the ED physician went to the resuscitation room to relay information and organize the trauma team. Clearly defined roles and responsibilities allowed trauma team members to perform preparation work at their own pace, even without the presence of the surgical team leader.

In contrast, the ECIC team does not have a division of labor as all team members share the same job title with identical responsibilities. This work arrangement has both positive and negative effects on their coordination. On the one hand, equal job title and training levels allowed team members to perform identical tasks, and thus, carry out complementary activities to assist each other. On the other hand, without delineated roles and responsibilities, team members often got confused about task ownership. For example, we frequently observed more than one ECIC team member simultaneously reaching for the phone or radio to answer an EMS call, causing confusion about the call ownership.

Overhearing. If team members are collocated, they can take advantage of working side-by-side to overhear conversations about ongoing activities, which in turn can trigger their own actions [18]. In the pre-hospital CIS, two of the four teams are collocated: ECIC and trauma teams. In the ECIC control room, when EMS calls came in through radio, other ECIC team members could overhear the call conversations, which provided opportunities for collaboration on call-taking and transport-arranging tasks. In several instances, we observed one ECIC team member answering an EMS call and the other calling the ED physician to relay the information.

Overhearing is also used by trauma team members. We previously found that co-present trauma teams leveraged overhearing to maintain awareness of ongoing activities during resuscitations [46]. In the present study, we observed that the overhearing mechanism not only helped team members perform tasks, but also stimulated group discussion, as shown in the vignette below:

An ED physician, surgical resident, radiologist and medication nurse assembled in the resuscitation room. The physician told the resident that they were having a trauma transfer. The radiologist overheard this and confirmed with the physician: "It's a transfer?" The physician answered: "Yeah. It's coming from [facility name], trauma stat. Yes, you need to be here." The radiologist continued: "But you just called it a trauma transfer?" The physician explained: "It is a trauma transfer. But it also is a trauma stat pending." Medication nurse overheard what ED physician and radiologist were saying, and asked: "Is the patient getting better? Did you want me to keep the PICU alerted?" The physician answered: "Yes, he is still going to have to go to the PICU and everything."

Oscillating Levels of Articulation Work

The pre-hospital CIS sets a number of requirements for articulation work. While the coordination mechanisms address the distributed and heterogeneous nature of the CIS, the levels of articulation work differ and are tied to the planned-for, unknown occurrence of trauma cases.

The EMS teams relay the context and content of a trauma case, as well as the ETA to the ECIC team, which then initiates the assembly of the ED and trauma teams. Although all EMS calls are critical, the urgency and speed of the work procedures vary with the nature of the trauma case, patient acuity, and the ETA. The levels of articulation work, therefore vary depending on the speed and amount of information that had been handed over: the more urgent the case, the scarcer and less precise information is, which in turn has its specific challenges for the CIS. Achieving common understanding and providing context for information were best facilitated by collocated actors using dense means of communication that fostered dialogue and awareness. The distributed, heterogeneous, and high-risk nature of the pre-hospital CIS limited these options and so articulation work varied: in the worst case, trauma team was incomplete and no information was available; in the best case, everyone was present and information was filtered, contextualized, and validated.

DISCUSSION AND CONCLUSION

We studied the process of pre-hospital communication as a "massively distributed" setting in which heterogeneous teams work together on a time-critical task. In doing so, we drew on the concept of CIS to better understand how information was relayed and put in common between the medical teams, and how this common understanding supported coordination. We found that teams faced many challenges in constructing the pre-hospital CIS, including difficulties in locating and assembling team members, communicating and interpreting information from the field, and reconciling the differences in team perspectives and information needs, all while having minimal technology support. These findings align with those from previous studies of pre-hospital work showing the lack of trust in EMS teams [4] and the challenges in achieving common understanding between EMS and ED teams due to inadequate technology support [29]. Where our study departs from previous work is in viewing the pre-hospital collaboration as a distributed and heterogeneous CIS that exhibits a novel combination of high-risk, time-critical activity with oscillating temporal rhythms. Using the CIS lens allowed us to gain a more nuanced understanding of the common grounding process in complex teamwork that is shaped not only by actors, but also by the environment and artifacts. It also allowed us to contribute theoretical innovations to the concept itself by adding new parameters that can be used to characterize multi-stage cooperation between distributed, heterogeneous teams. We next discuss our contributions to the CIS framework and how they relate to general CSCW concerns beyond the CIS literature. We conclude with design opportunities for supporting highly distributed and heterogeneous teams in high-risk settings.

New Parameters for Characterizing a CIS

Reflecting on the nature of the pre-hospital CIS and tying our findings to prior work, we propose to extend the framework by adding two new parameters: the scalability of collaboration and the multiplicity of information spaces.

The Scalability of Collaboration

Our study showed that the scale of collaborative work matters. The scalability of collaboration has two aspects: the number of participants involved, and the number of stages required for completing collaborative work.

First, the number of participants is an important factor in collaborative work and is closely related to two other CIS parameters—the multiplicity of webs of significance and degree of distribution. The larger the number of participants in a CIS, the more varied are the webs of significance—not only because the number of professions and disciplines may increase, but also because the number of work settings, and hence the differences between contexts of work and information, may increase as well. More articulation work is therefore required to accommodate different perspectives. Similarly, the higher the degree of physical distribution in a CIS, the more complex work arrangements and technology support are needed. For example, mechanisms for supporting collaboration in online environments need to dramatically scale to support large-scale distributed collaborative work [12]. In the wastewater plant, there were only few participants, and information sharing could be done ad hoc during breaks [7]. At the hospital ward, there were more collaborators, but information sharing and coordination were successfully managed by scheduled meetings and a stable web of coordinative artifacts across fewer webs of significance (professions) [9,28]. In the oil-well planning case, however, the extreme heterogeneity of collaborators, information systems and data formats led to "collaboration rooms" with several large screens to allow for the shared understanding of information [30]. The urgency of pre-hospital tasks do not allow for such rooms.

Second, the asynchronous collaboration and communication in the pre-hospital CIS may lead to a multi-stage arrangement of a CIS. For example, communication and coordination in the pre-hospital space are temporally separated. To establish common understanding between the information originator (EMS team) and the information recipient (trauma team), several interrelated, asynchronous, and small-scale CISs are constructed. Specifically, the EMS and ECIC teams first construct a CIS to understand the injury mechanism and patient status. Once established, this common understanding is critical for the subsequent rounds of communication between the ECIC and ED teams, and ED and trauma teams because it provides the foundation for accurate information sharing throughout the process.

This multi-stage CIS appears to be caused in part by limitations of the communication technologies, so it would seem opportune to allow for more direct ways to put information in common. The present setup poses several challenges. First, different data formats and modes of communication may affect the accuracy of information as it moves between spoken and written. Second, current artifacts (e.g., phones, pagers, the FirstNet system, paper notes) do not integrate well across stages. Third, different information types are needed as the information moves from one team to another. Contextual information about the incident site is of interest to trauma teams, and ETA is of interest to the ECIC team. However, once the patient is in the hospital, context and ETA become irrelevant for the trauma team, and are being replaced by other information, like patient vitals, which is now crucial. Viewed from this perspective, the resuscitation room is a typical case of an in-between site [10]. In the wastewater plant [7] or the hospital ward [9], these challenges are less pronounced because of the stable rhythm and support for collaboration. However, the challenges in the pre-hospital CIS are similar to those of the oil-well planning [30], where "collaboration rooms" were setup to support common grounding.

The Multiplicity of Information Spaces

A CIS often consist of several centers, peripheries and overlapping zones, which may be loosely or tightly connected. Connections in the oil-well planning case were so loose that a "collaboration room" was necessary to allow for a CIS to temporarily emerge [30]. In the pre-hospital CIS, a combination of personal, local and common artifacts supports multiple information spaces that then intersect to form the entire CIS.

Personal information spaces are formed by individuals based on personal artifacts and mental capacity (e.g., notes, notepads, short-term memory). Local information spaces allow actors to share information through common artifacts, e.g., when members across different teams communicate via phones, the FirstNet system or pagers. When collocated, such local information spaces become zones or peripheries: the information space and the spatial arrangement of interactions and artifacts overlap. For example, the ECIC control room with its artifacts and workers represents a local information space and a center of the pre-hospital CIS for the ECIC team members. Similarly, ED staff, patients, equipment and artifacts constitute the local information space of the emergency department. Personal and local information spaces are not equally accessible to all collaborators of the CIS, but both have a critical role in contributing to the construction of the entire CIS. Understanding the interplay between these information spaces can help inform the design of technologies to support information sharing and work coordination.

Beyond CIS: The Centrality of Interpretation Work

A central concern in studying CISs has been the difference between putting information in common, making sense of this information in the context of local work practices, and achieving common understanding. Similar to "articulation work" [33,39], "interpretation work" was considered a critical part of the process because putting information in common is typically followed by making that information meaningful in the context of actors' own work practices, and in overall cooperation [28,33]. In collocated CIS, interpretation work benefits from face-to-face interactions, such as being able to see actions of others or perform quick query-response interactions, like those observed in the overhearing vignette from above. In distributed CIS, however, these resources are not available and a key challenge for CSCW is to effectively support interpretation work in such environments [33]. This challenge also

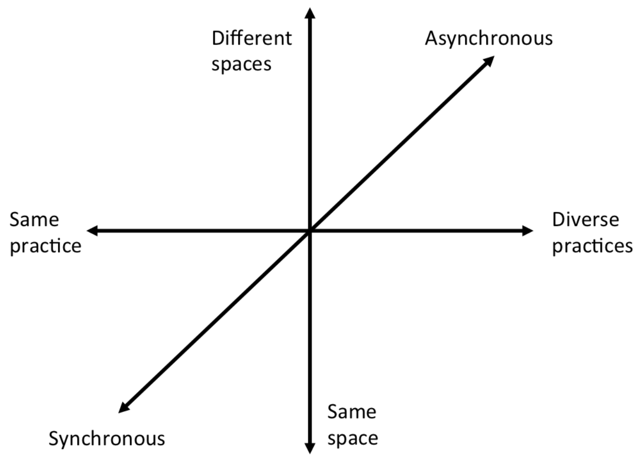

Figure 2: A time-space-practice matrix of collaborative work.

pertains to collocated CIS where groups with different frames of reference cooperate [28].

In the pre-hospital CIS, putting information in common was challenging, as evident in ED physicians' comments about EMS teams' reports being too detailed, incomplete or imprecise. In ED and trauma teams' view, EMS teams did not understand their information needs and perspectives. However, we also observed a discrepancy in the information needs among ED physicians, as evident through the lists of three things they needed to know: in one case the list included "what happened, if the EMS did anything, and the state of the patient;" in another, it included "is there a physiological change in the patient, is there a fracture, and is there a mechanism."

Furthermore, interpreting information was complicated by disparity of professional backgrounds and local work contexts, as reflected in different interpretations of the word "lethargic" by EMS teams and ED physicians. A lack of understanding of the EMS team's context and perspective made the interpretation work even more challenging. EMS paramedics are not physicians, yet they need to address a variety of contingencies: getting access to patients, moving patients into the ambulance, and stabilizing patients while in busy traffic. Their information and coordination needs during pre-hospital care differ from what is needed upon their arrival to the hospital—an easily accessible patient available for treatment, along with critical patient information as defined by the trauma team's needs. EMS teams may not even know why some information is critical, just that they have to provide it. From the EMS teams' perspective, in the pre-hospital context they are "experts" saving lives, but as they enter the hospital, they become "servants" merely delivering patients and requested information [4]. Even then, ED and trauma teams often did not trust EMS actions, which they thought lacked pediatric experience and clear reasoning behind en route treatments.

Hence, in the pre-hospital CIS and in many other collaborative settings, interpretation work that makes sense of information in the context of local work practices and the overall collaboration is crucial. This type of interpretation work is particularly difficult when the scale of collaboration is large and there are multiple CISs. Other studies of distributed collaboration have also discussed these challenges (e.g. [8,17,24,27]). Even so, Johansen's time and space matrix [19] continues to be perceived as sufficient for classifying cooperative work using the prevalent 2x2 collocated vs. distributed and synchronous vs. asynchronous matrix. [21]. To foreground the centrality of interpretation work, we propose adding *work practices* as a new dimension to the time-space matrix (Figure 2). We drew from the Söderholm's practice-environment matrix [37] that was created to help make sense of all possible collaboration combinations between future users of telepresence technology in medical work.

In this new "time-space-practice" matrix, the practice dimension corresponds to the multiple webs of significance found in distributed and heterogeneous CISs. By practice, we mean actors' experiences, knowledge and frames of reference in relation to their professions (e.g., the level of medical training) and the collaborative work context (e.g., being part of an EMS team and a pre-hospital CIS). The benefit of the classic 2x2 matrix is that the resulting four dimensions provide an overview of the possible time-space configurations. But as such, it makes the centrality of interpretation work in collaboration invisible. In contrast, our modified matrix puts the interpretation work front and center, highlighting the importance of whether or not collaborators are involved in the same work practices, which makes achieving the shared understanding more likely. The resulting eight dimensions provide a useful heuristic for achieving overview of and perspective on cooperative work.

Design Opportunities for the Pre-Hospital CIS

Information sharing and coordination occurred in all stages of the pre-hospital CIS, but only some were supported by technology. This limited support posed several challenges in constructing the CIS. Using our findings, we next discuss two design opportunities to better support information sharing and coordination in the emergency medical work.

Making Interpretation Work Visible through Visual Collaborative Technology

Current workflow and system infrastructures in the pre-hospital CIS require multiple steps in the communication chain, but do not support clarification through, say, dialogue. This setup increases the chance of information misinterpretation, potentially leading to adverse patient outcomes and inefficient teamwork. The use of visual collaborative technology may help address these challenges in two ways. First, a visual system could facilitate sharing of the contextual patient information that is often difficult to describe and document during patient transport. Current communication between pre-hospital and hospital teams is limited to verbal exchanges only. Because contextual information conveys the larger context in which the information was generated, it is often needed by trauma teams to prepare for patient arrival. Second, it is important to establish trust between EMS and ED teams, as well as between EMS and trauma teams. A visual system would allow EMS team members to highlight injuries and explain how they treated patients, making ED and trauma teams more open to trusting and accepting the EMS interventions.

Visual technologies, such as video conferencing and telemedicine have been shown effective in supporting collaboration among distributed actors [16,36]. The healthcare sector is increasingly adopting these systems to support remote consultation between clinicians [15], as well as communication between EMS and ED teams [36]. The role of the ECIC team in validating and filtering information is important, but direct transmission of information from the field to medical experts may also be beneficial, as our interviews with members of the ED and trauma teams confirmed.

Making Information Accessible through an Integrated Data Documentation and Presentation System

We observed many challenges in communicating information from the field and between hospital teams, as well as in timely and accurate information interpretation. Currently, EMS paramedics use either paper or an electronic system for documenting pre-hospital information that hospital teams cannot access in real time. Furthermore, technology support for presenting the pre-hospital information to ED and trauma teams is also limited. An integrated system with a data-capturing tool for the field and data presentation terminals for the hospital may help address these challenges. Below we discuss four design issues with this system.

First, our study showed that hospital teams often found the information reported by EMS teams unreliable—the initial verbal reports were either incomplete or overwhelmingly detailed, suggesting there is a need to support the process of achieving common understanding of perspectives and information needs across different teams. The design of a data-capturing tool for EMS teams should consider information needs of the hospital teams. The ranking of different information types expressed by ED and trauma team members can help prioritize the items for data input.

Second, standardizing EMS reports does not necessarily mean that data input should be static. Rather, it should be dynamic and adaptive to different patient injury mechanisms. While each trauma patient is unique, there are commonalities between cases due to the same or similar injury mechanisms. This domain characteristic provides an opportunity to design interfaces for data-capturing tool where EMS teams could toggle between different scenarios, each asking for a customized set of information items.

Third, an important challenge we observed was locating the EMS team and patient en route to the hospital. Knowing temporal information like estimated arrival time (ETA) allows for timely preparation work in the ED and resuscitation rooms. Embedding GPS technology into the data-capturing tool would automatically detect the location of the EMS team (and the patient) and compute the ETA by also taking into consideration real-time traffic.

Fourth, terminals (e.g., smart phones, embedded displays or desktop computers) used by ED physicians and trauma team members can be based on web technology, enabling information access anytime and anywhere. Earlier attempts at providing interactive systems for presenting the pre-hospital information in real time showed feasibility of this approach [2,20]. Making the pre-hospital information accessible to the hospital teams could support the construction and management of both personal and local information spaces. For example, instant and visual access to patient data as trauma teams assemble in the room could obviate the need for repeating the patient story every time a new team member enters the room.

Although the systems we envision cannot address all of the challenges we identified, they could help translate the pre-hospital narratives into a meaningful, easy-to-absorb data presentation for hospital teams. Most importantly, the systems would help increase the accuracy and efficiency of establishing common understanding between the pre-hospital and hospital teams. At the same time, we acknowledge that approaches to these challenges must be socio-technical [29], and may also include implementation of standard procedures and policies for handovers between different teams involved in the process [1].

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