Data Work and Decision Making in Emergency Medical Services: A Distributed Cognition Perspective

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Emergency medical services (EMS) teams are first responders providing urgent medical care to severely ill or injured patients in the field. Despite their criticality, EMS work is one of the very few medical domains with limited technical support. This paper describes a study conducted to examine technology opportunities for supporting EMS data work and decision-making. We transcribed and analyzed 25 simulation videos. Using the distributed cognition framework, we examined EMS teams' work practices that support information acquisition and sharing. Our results showed that EMS teams leveraged various mechanisms (e.g., verbal communication and external cognitive aids) to distribute cognitive labor in managing, collecting, and using patient data. However, we observed a set of prominent challenges in EMS data work, including lack of detailed documentation in real time, situation recall issues, situation awareness problems, and challenges in decision making and communication. Based on the results, we discuss implications for technology opportunities to support rapid information acquisition, integration, and sharing in time-critical, high-risk medical settings.

CCS Concepts: • Human-centered computing → Collaborative and social computing → Empirical studies in collaborative and social computing

Additional Keywords and Phrases: documentation; data work; electronic health record; teamwork; decision making; distributed cognition; emergency medical services; pre-hospital care; video analysis

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1 INTRODUCTION

Emergency medical care is a fast-paced and dynamic process that addresses severe illnesses or life-threatening injuries (e.g., trauma, stroke, and seizure) [1]. Following an incident, Emergency

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Medical Services (EMS) teams are dispatched to provide urgent medical care in the field and transport patients to the nearest point of definitive care (e.g., a hospital). There are nearly 20,000 reported EMS agencies providing emergency care to over 37 million patients annually in the United States [2]. Management of critically-ill patients requires rapid and accurate information acquisition and decision making [1]—EMS providers (e.g., paramedics) need to quickly seek, collect, integrate, and manage various types of information about the patient's status, needs, and treatment activities (pre-hospital information) from multiple sources. In addition, EMS providers need to share pre-hospital information with emergency department (ED) teams at the receiving hospital to help them better anticipate the patient's needs and allocate necessary clinical resources before patient arrival [1, 3-5]. Despite its criticality, there is a lack of effective approaches by which pre-hospital information is accrued to allow for easy integration and analysis in real time for effective clinical decision making.

Unlike ongoing care in hospital wards, the information acquisition and integration in emergency care is performed during a short and highly intense process (e.g., within a scale of minutes and even seconds) [6]. However, the highly dynamic and interruption-driven nature of EMS work at the point of accident ground poses significant challenges for accurate and timely data acquisition and documentation [7]. For example, a study reported that 40% of the data fields on an ambulance medical record were either left blank or filled in erroneously [8]. Similarly, another study found that 28% of EMS records were missing patient's physiologic data [9]. Even more concerning is that EMS teams do not always have a dedicated role for data acquisition and documentation—a cognitive- and time-consuming task which is usually performed by a scribe person (e.g., nurse recorder) in other medical teams. These unique challenges and characteristics of EMS work often result in difficulties in acquiring information needed for decision-making and failures in communication with hospital teams. Therefore, it is of utmost importance to understand patterns and information flow in EMS work to address these challenges. However, to date, there is limited research examining how to support real-time information acquisition and decision making in the field.

The long-term goal of this research is to design and develop technology solutions to support the capture and sharing of pre-hospital information in real time. The first step to achieve this goal is to understand the work practices and information behaviors of EMS teams and the challenges they face in their data work. In this paper, using distributed cognition (DC) as an analytical framework [10], we examined EMS teams' verbal communication and work practices related to information acquisition, recording, and sharing. By reviewing and analyzing the videos of 25 EMS simulations, we found that EMS teams relied on various mechanisms (e.g., verbal communication, tacit monitoring, and external cognitive aid) to distribute cognitive labor and coordinate work. We also observed a set of challenges, including lack of detailed documentation in real time, situation recall issues, situation awareness problems, and challenges in decision making and communication. We conclude by discussing the implications of this study from three perspectives: 1) the application of the distributed cognition framework in examining complex social-technical systems, 2) technology opportunities for supporting real-time data collection and decision making in fast-paced medical settings, and 3) EMS team training.

Our contributions to the CSCW community are three-fold: First, we contribute a detailed account of EMS work practices and faced challenges in real-time information acquisition and decision making, which remain understudied in the CSCW community. Second, we presented a case study of using the analytical models of distributed cognition to examine highly dynamic and complex socio-technical systems. Lastly, our study informs design implications for technology solutions that support rapid information acquisition, integration, and sharing in time-critical, high-risk medical settings.

2 BACKGROUND AND RELATED WORK

In this section, we first provide an overview of EMS work and then describe a strand of literature on data work, decision-making, and information acquisition in dynamic medical settings. Lastly, we introduce the theoretical framework that guides this study—distributed cognition (DC)—and the reasons for choosing this framework.

2.1 EMS WORK

Emergency Medical Services (EMS) teams are dispatched to the field to provide emergency care once activated by an incident that causes severe illness or injury. In the United States, EMS services can be based in a fire department, a hospital, or a non-profit organization (e.g., rescue squad). There are usually two types of EMS personnel, emergency medical technician (EMT) and paramedic. EMT training focuses on basic life support techniques such as cardiopulmonary resuscitation, oxygen administration, and wound treatment. In contrast, paramedics need to undertake more extensive trainings to be qualified for performing advanced life support procedures, such as administering medication and fluids, resuscitating patients, and providing breathing support and advanced airway management. Both EMTs and paramedics also take special trainings to act when a mass casualty incident (e.g., disaster, massive shooting) happens. In particular, some EMS agencies prepare their providers at all levels to work with first responders from other agencies, many of whom they do not normally come in contact with [11].

EMS teams are organized flexibly in reaction to changing situations. Usually, before a medic unit leaves the base, the director or dispatcher decides whether one ambulance staffed with two EMS professionals can handle the situation or if a backup ambulance is necessary. For a major incident, multiple units may need to be dispatched to the scene. Typically, the EMS dispatch center provides incident information to help EMS teams determine which equipment to take, what to plan for the situation, and what complications to expect. At the scene, EMS providers have to assess the situation and make decisions quickly. They usually use three diagnostic tools: interviews, physiological evaluations such as electrocardiograms (ECGs), and physical assessments (e.g., primary and secondary survey). These evaluation procedures and tools could help EMS teams decide treatment and the next most pressing task. For critical procedures or ambiguous cases, EMS teams can choose to call ED physicians at the receiving hospital for online medical control. However, in the meantime, EMS providers are often busy with patient care, complicating many of their activities, including data gathering and documentation.

Much work in EMS has focused on improving work efficiency and addressing human factors of EMS working environment (e.g., [10, 12-15]). For example, Kristensen, et al. [12] employed a participatory design approach to examine the features of EMS work and technology use in different emergency situations. Their work contributes design implications for new interactive technology systems to support multidisciplinary work in future EMS practice. Despite these efforts, the EMS domain remains understudied in the CSCW field—there is a lack of empirical studies to examine the issues and challenges in EMS work [12]. Since many of the challenges in EMS work are tied to data work—collecting, identifying, using, and sharing patient information in the field—our research focuses on this long-standing yet unsolved problem. This study aims to gain a comprehensive understanding of how EMS teams communicate and collaborate to acquire and integrate pre-hospital information and what challenges exist in this process. These insights will inform the design of novel technologies to better support EMS teamwork.

2.2 Data Work in Healthcare

Data work refers to the effort involved in "*creating, collecting, managing, curating, analyzing, interpreting, and communicating data*" [16, 17]. In the healthcare field, care providers use patient data for various purposes, such as quality improvement, research, patient care, and communicating with other care members or teams. A central theme of this line of research centers around understanding how patient data is collected, contextualized, shared, and used [18, 19]. For example, Pine [20] uncovered how medical records coders and clerks used situated judgement and calculation to create administrative data from clinical records (e.g., birth certificate data) for secondary uses. In a systematic review, Bossen, et al. [19] pointed out that medical scribes have emerged as a new data work occupation as a response to the increased demands for documentation (i.e., through EHRs). Unlike the studied clinical scenarios and despite the advent of electronic patient report modalities, our study setting is unique in that there is no dedicated or emerging role for documentation and data collection. The present study contributes to the research on data work by investigating how such fast-paced care teams with no data work occupation collect, manage, share, and communicate data.

2.3 Decision Making in Time-Critical Medical Settings

Rapid and accurate decision making in time-critical medical settings is of utmost importance. Many research efforts have been devoted to developing computerized clinical decision support systems (CDSS) for hospital-based critical care teams, such as intensive care (ICU) [21], surgical teams [22], and trauma resuscitation teams [23]. However, only a few attempts focused on developing decision support systems for EMS teams who work outside of a hospital. For example, Mentler and Herczeg [24] developed a tablet-based cognitive artifact for enhancing situational awareness of ambulance incident commanders in cases of mass casualty incidents. The system interface has visual charts to illustrate the number of patients in specific triage categories. The system also supports personal note taking. Their study highlighted several usability and ergonomic challenges for implementing and using CDSS in the context of pre-hospital care, such as difficulties arising from wearing gloves, or accidentally touching a device while working with dirty hands [24]. Another example is SAFER 1 [25], a handheld CDSS for EMS providers to assess and determine care needs and plan for older patients. A significant step required for using this system is recording the patient's past history and examination results into the electronic health record (EHR) for recommendation generation. Despite its promising features, the study showed that EMS providers used the system with only 12.4% of eligible patients [25]. In a similar vein, Hagiwara, et al. [26] investigated the effects of a CDSS on pre-hospital stroke care and concluded that the system can improve patient assessment, decision making, and compliance to process recommendations. However, several negative effects emerged through the testing process, such as increased on-scene time, ineffective documentation, cognitive burden of using the system, and changed workflow.

A significant disadvantage of these computerized clinical decision systems is that data entry was manual, requiring additional work and time from emergency care professionals who were already busy with unpredictable and cognitively consuming tasks. As such, few decision support systems have been used in clinical practice [27]. These challenges motivated researchers to investigate how to improve information acquisition in time-critical healthcare settings. Similar to other hospital settings [28-32], EMS practitioners often use informal documentation methods, such as taking quick notes on a rubber gloved hand or a piece of scrap paper [33]. However, this documentation practice may result in information loss (e.g., rubber gloves do not have the affordance of documenting an accurate description of the sequence of events and medical treatments; gloves can be easily contaminated or soiled and need to be discarded) [33].

2.4 The Use of Electronic Health Records in Time-Critical Medical Settings

As the push toward digitizing medical work continues, some fast-paced, critical care settings are increasingly using EHR systems. Not surprisingly, a gap still exists between the formal EHR documentation and actual clinical workflow [32]; that is, the EHR system is not able to document procedural information, capture key information, and present information according to the actual clinical workflow [32, 34]. For example, one study examined the use of an EHR system in an ICU and found that the system decreased the time ICU nurses spent on patient care compared to manual paper charting [35]. In a similar vein, Sarcevic and her colleagues [27, 36] examined the use of an EHR system in trauma resuscitation and found that the use of EHR in this time-critical domain resulted in inefficiencies and incomplete real-time data capture.

In our study context, EMS teams face similar issues in the use of electronic systems for real-time data collection and documentation. For example, Tollefsen, et al. [7] developed and evaluated a menu-driven electronic system for EMS providers to document field information (e.g., vital signs, demographics, and medical history). They noted several barriers in the effective use of this system, including medical professionals' resistance to using technology and the gap between data entry methods and EMS workflow. In another study, Hertzum, et al. [37] described the lessons learned from implementing an electronic ambulance record by highlighting several key challenges: exceedingly time consuming in using the system, complicated data entry across too many screens, integration issues with the hospital system, and delays in addressing recurring technical problems.

In addition, several commercial electronic systems, such as emrCharts [2] and EmergencyReporting[3], have been developed to help structure data collection, providing many data fields for detailed data entry. These systems, however, are rarely used at the point of the accident or during transport [38]. Three explanations may account for the limited use of these systems in real time. First, EMS providers usually engage in complex tasks that are unpredictable, time-critical, and cognitively consuming, with limited time to use handheld data entry devices. Second,

[2] www.emscharts.com
[3] info.emergencyreporting.com

the use of these systems may increase the cognitive burden and result in a higher workload, especially if the workflow of EMS is not considered at the point of design [39, 40]. Third, during patient transport, one provider is in the back of ambulance providing care while the other is driving, making real-time documentation very challenging.

Therefore, we argue that the specifics of work practice for data collection need to be considered before designing electronic documentation systems for EMS practitioners, because the documentary practices and overall workflow of pre-hospital care are intrinsically intertwined [33]. However, few studies have examined the workflow within which EMS providers collect and document patient data. Our work contributes to bridging this knowledge gap.

2.5 Theoretical Framework: Distributed Cognition

Distributed cognition (DC) is a theoretical framework developed by Hutchins [41] to illustrate the distributed nature of cognition. Using the example of how the team of a large vessel performs the navigation task, Hutchins [41] presented DC as a view on how information is transformed and propagated within a socio-technical system. Later, Hollan, et al. [42] expanded the concept by suggesting three ways in which cognition may be distributed: 1) across the members of a team, 2) between internal and external structure, and 3) through time so that earlier events may transform the nature of later events. The theory of DC has been used to analyze fast-paced medical domains, such as emergency medical dispatch [10] and emergency coordination center [43].

Even though DC is a well-known theory in CSCW, for much of its history, how to use this theory to analyze social-technical systems has remained largely opaque [44]. As Furniss and Blandford [10] stated: "*Most prior work on DC has been largely descriptive, and some researchers have interpreted it as principally a descriptive theory.*" (p. 28) They proposed a codified framework with a set of principles and models, namely Distributed Cognition for Teamwork (DiCoT), to analyze the strengths and weaknesses of a socio-technical system from a DC perspective. Since then, a few studies have applied DiCoT to the analysis of safety-critical medical systems such as mobile healthcare work [45] and ICU [46, 47].

In this study, we used three interdependent models of DiCoT to examine information flow during EMS work. These three models are physical layout, information flow, and artifacts. The physical model describes physical-level factors (e.g., things that can be physically heard, seen, and accessed by individuals) that directly impact people's cognitive space. The information flow model focuses on the communication between the participating team members, while the artifact model represents how artifacts and their representations within a work setting support (or fail to support) cognition. These three models provide a holistic analytical view to examine a socio-technical system and identify sources of weakness in that system. We chose this framework because its focus is on the cognitive processing among people and artifacts rather than the cognitive properties of individual people. Therefore, it is useful for studying EMS work, a complex socio-technical system where most representations of the patient status and team activities are managed using observable social (e.g., paramedics' inquiries and verbal reports) and material elements (e.g., paper and computerized artifacts). Another goal of using DiCoT in this study is to examine the ability of DiCoT in evaluating socio-technical healthcare systems, and to advance the effort of bringing this analytical framework to a broader audience.

In this work, our analysis centered around verbal communications and interactions between EMS providers, and the artifacts used for information acquisition and documentation. Through detailed analysis, we were able to identify the challenges in EMS teams' cognitive processing, and the use of coordination mechanisms [48, 49], including both material (e.g., artifacts) and immaterial (e.g., short term memory, situation awareness) mechanisms [3, 50, 51], to coordinate tasks and distribute cognitive labor.

3 METHODS

3.1 Dataset

This is a secondary analysis of video recordings of 25 simulations performed in an urban fire-based EMS agency in the U.S. western mountain region. The original investigation focused on evaluating team-based care of pediatric emergencies following medical trainings, leading to a total of 140 simulations being conducted and videotaped. On average, 8 simulations were conducted each day of data collection. The present study took a random sampling (n=25) of this large dataset. The simulations utilized high-fidelity patient mannequins with advanced features such as breath sounds and simulated ECG rhythms, allowing for continuous monitoring of patient status and real-time physiologic response to provider interventions. Licensed EMS providers from the agency were recruited to participate in three high-fidelity simulations over six months. The simulation scenarios included a 15-month-old seizure, a 1-month-old with hypoglycemia, and a 4-year-old clonidine ingestion. The clinical scenarios varied by patient age, weight, clinical condition, and required treatments. The participants of the simulations are EMS providers who staff either an ambulance or a fire truck in their daily job. Most of the participants have more than 10 years of experience. Some of the participants chose to attend more than one simulation. Each simulation team had 4-6 members with one paramedic serving as the team leader. Each participant may not always have the same role if they participated multiple times. For example, the paramedics switched roles on occasion with different team members taking the role of team leader. There were no roles removed during the scenarios and simulation teams were instructed to carry out each scenario as they normally would in an actual event. In this paper, we refer to the study participants as paramedics.

Three video cameras with audio capabilities captured each simulation, allowing us to obtain a comprehensive view of activities carried out. One camera captured the patient's overhead view and the other captured the foot side of the patient. The third camera provided a zoom-out view of the entire team. The view of vital signs monitors was also captured and included in the video recordings. The length of videos varies, ranging between 9 and 14 minutes (the average length is 11 minutes). The videos were transcribed verbatim using excel sheets to provide a linear list of the conversations and performed tasks. As shown in Table 1, each video transcript includes time stamps, conversations, tasks, speaker (who was speaking), subject (who the speaker was talking to), and action (who was performing what task). One researcher (R2) transcribed the videos while two other researchers (R1 and R3) performed quality control to ensure the transcription was correct. These researchers have qualitative research and design background, while also being briefly trained to interpret medical procedures and terminologies in the context of EMS.

Table 1: Excerpt from a coded transcript (Note: due to space limit, other columns such as "non-verbal cues", "observed challenges", and "notes" are excluded from this table).

Time	Speaker	Subject	Dialogue	Action	Comm. Code	Info. Source	Info. Type (L1)	Info. Type (L2)	Action Code
2:40	TL	PR1	How are the lung sounds?		Request Information				
2:46	PR1	TL	The sounds are clear.	PR1 listens patient's chest using stethoscope	Respond to Inquiries	Co-worker	Physical Findings	Breathing	Physical Exam
2:48	TL	PR1	Clear? Okay.		Ack. Information				
2:50	PH	TL	Sitting at 95. Pulse ox. Heart rate's raising up a little bit to 194.		Report Information	Co-worker	Physical Findings	Vital Signs	

3.2 Video Review and Data Analysis

Two researchers (R1 and R2) first reviewed four videos randomly selected to develop a coding scheme. Based on the DiCoT framework [10], we focused our analysis on physical arrangements, communicative and work practices, and artifacts used, while also paying special attention to the challenges related to information acquisition and decision-making in the field. The initial list of codes was discussed among researchers to determine which codes to keep, merge, or discard. After the coding scheme was set, we created a codebook defining each code to standardize the coding process. Our final codebook contained five categories, including verbal communication, type of communicated information, information source, action, and challenges. For example, codes related to verbal communication included *assign tasks*, *request information*, *report information*, *acknowledge information*, *relay information*, *provide clarification*, *respond to inquiries*, *state decision*, *discuss decision*, *summarize care process*, and *report to hospital*. Action codes included *physical examination*, *measurement*, *instrument reading*, *equipment setup*, *medication administration*, and *note-taking*.

R1 and R2 then coded the remaining transcripts using the developed codebook. Specifically, R1 coded all 25 simulation videos while R2 coded 30% of the total simulations (n=8). Cohen's Kappa coefficient was used to determine the inter-rater reliability by comparing two researchers' codes on the commonly coded transcripts. The coders presented a "substantial" agreement on the codes (kappa value is 0.7). Disagreements on the analysis were discussed and resolved during weekly group meetings. An excerpt of a coded transcript is shown in Table 1. Using the second row (time stamp 2:46) as an example, PR1 (a medication paramedic) reported the status of patient's breathing after checking the patient's chest using stethoscope. Since PR1 reported the information in response to the team leader's question, we coded this verbal communication as "Respond to Inquiries". The high-level (L1) type of reported information was "Physical Findings", and the lower level (L2) of information category was "Breathing". The code for PR1's action was "Physical Exam".

In addition, we also performed quantitative analysis. For example, we calculated the frequency of different types of verbal communications and tasks for each role over 25 simulation events. We also analyzed the frequency of observed challenges in all 25 simulations. The quantitative analysis augmented our qualitative observations, enabling us to obtain an in-depth understanding of EMS teamwork.

4 RESULTS

Timely and accurate information acquisition is never easy, especially when a dedicated role for data collection and integration does not exist. In this section, we first draw on the DiCoT framework (e.g., physical layout, information flow, and artifact) [10] to describe the mechanisms and work practices for distributing cognitive labor in the field, which allowed EMS providers to effectively collect, share, and manage patient data under time pressure. Then we present the challenges that resulted in inefficient information flow and teamwork.

4.1 Mechanisms for Distributing Cognitive Labor in the Field

4.1.1 Physical Layout. Even though team composition (e.g., number of members in an EMS team) may vary across different EMS agencies, in our study context, paramedics were strategically positioned around the patient bed based on their primary responsibilities (Figure 1a). For example, the paramedic who was responsible for managing the patient's airway (airway-paramedic) was usually at the head of the bed. This location allowed him/her to easily perform treatment for airway and closely monitor patient breathing. The paramedics in charge of medication and fluid administration (medication-paramedic) usually sit on both sides of the patient to not only facilitate the establishment of intravenous (IV) or intraosseous (IO) access and administration of medication but also to ensure easy access to the stored materials (e.g., equipment, medications) on both sides of the ambulance. The team leader usually sits next to or face-to-face with the patient's parent or guardian at the foot of the bed where the vital signs monitor was always placed (Figure 1), allowing for easy communication with the patient's parent. Also, with proximity to the vital signs monitor, the team leader could closely monitor the patient's status and determine intervention promptly.

Overall, we found this team composition and physical layout worked well for supporting each paramedic's "horizon of observation" (e.g., what they can see or hear) [41]. We also found that this collocated setting allows for 1) subtle bodily supports—using body gestures and movements to support cognitive processes (e.g., pointing at a specific part of the patient body while discussing symptoms or physical findings) [41], and 2) tacit monitoring or overhearing of each other's work—a widely used mechanism for coordinating task and maintaining awareness in dynamic teamwork settings [52].

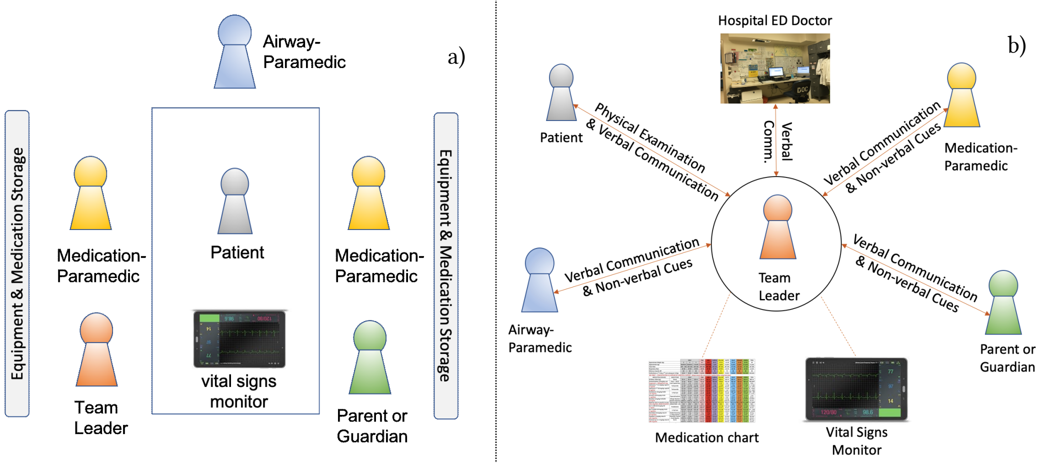

Fig. 1. a) A typical EMS team positioning and physical layout in the simulation; b) A simplified illustration of the distributed cognition of EMS team. Here we can see that the team leader acts as an information hub, collecting and integrating a variety of information from different sources and “cognitive labors”.

4.1.2 Information Flow. We identified 16 information types that were often communicated among paramedics and grouped them into four major categories, including demographics (e.g., age and medical history), physical findings (e.g., vital signs, pulses, breathing, consciousness, symptoms, and changes of patient status), mechanism of injuries (e.g., how the incident happened), and treatments (e.g., medication, fluid, and oxygen).

We found that the information reporting/sharing was strongly associated with the tasks paramedics were performing even though there was no pre-defined role for each paramedic (Figure 2a, bottom). For example, the team leader usually talked to the patient’s parent or guardian to obtain patient demographics and how the incident happened. Therefore, team leaders shared such information with the entire team. In contrast, the physical findings and treatments were usually shared by the medication-paramedic and airway-paramedic since they performed hands-on patient examination and treatments most of the time. Regarding who requested what, paramedics often requested patient’s medical history and mechanism of injury, real-time vital signs, and medication during the care process (Figure 2a, top). Another interesting observation is that airway-paramedics requested vital signs information more often than other paramedics (e.g., medication-paramedic). One possible explanation is that it was not easy for them to clearly read vital signs information from a distance because they sit at the head of the patient bed while the vital signs monitor was placed at the foot of the bed (Figure 1a). This can be considered a negative effect of current team positioning and spatial arrangement of the artifacts.

The dominant form of data collection and sharing in EMS work is verbal communication. Inquiries and responses appeared to be the primary means for maintaining the division of cognitive labor (Figure 2b). We found that team leaders made the most inquiries (averaged 19 instances in a simulation session). In particular, our data shows that team leaders requested almost all information types more frequently than others. It is not surprising since team leaders needed to collect and integrate different types of information to make decisions (Figure 1b). We also found that team leaders were also the top information providers since they often responded

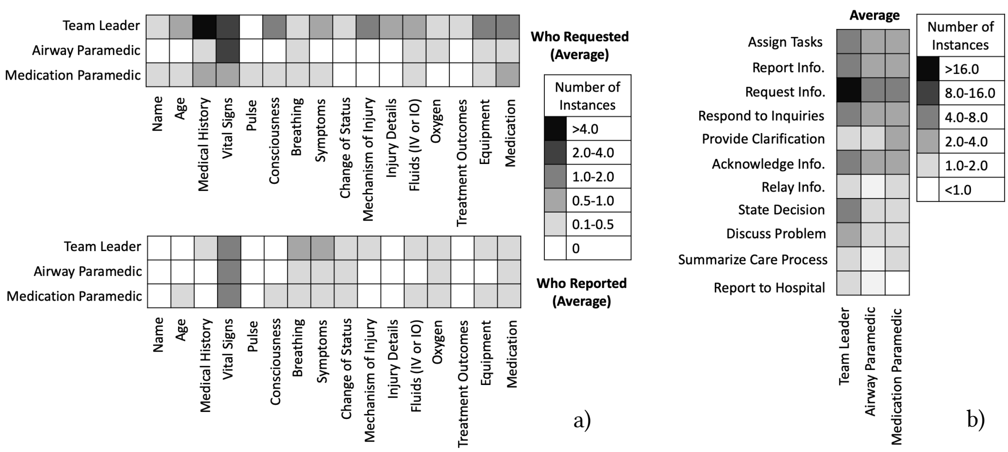

Figure 2: a) Frequency of who requested or proactively reported what information, by role, averaged over 25 simulation events; b) Frequency of verbal communications and tasks, by role, averaged over 25 simulation events.

to inquires based on the information they acquired earlier (on average, team leaders responded to inquiries 6 times in a simulation, compared to an average of 3 instances by other members). For example, since the team leader usually talked to the patient's parent, he/she was often probed by other paramedics about information on patient demographics or mechanism of injury.

In addition to inquiries and responses, we also observed proactive information reporting. This work practice is similar to the concept of "talking to the room" in [53], referring to undirected talk and sharing relevant information to the entire team or the room at large. Similar to [53], we also observed both information-related and action-related reporting. The former refers to the sharing of interpretation and observation (e.g., "the patient's breathing is improving."), while the latter is related to self-reporting the performance of on-going task (e.g., "I am going to administer IV fluid."). Such proactive information sharing and reporting is an important coordination mechanism, allowing users to maintain awareness and coordinate work dynamically [54].

Overall, EMS team members primarily relied on "articulation work" [55, 56] to facilitate information flow across paramedics. We also found that team leaders had more communicative instances than other members, suggesting that the team leader was the "information hub" of an EMS team (Figure 1b). They needed to collect and integrate various information from multiple sources (including artifacts and co-workers) in real time while working on hands-on tasks (e.g., patient examination) from time to time. This high workload poses significant challenges in their work. Next, we describe how paramedics, especially team leaders, utilized external cognitive aids to maintain the working memory.

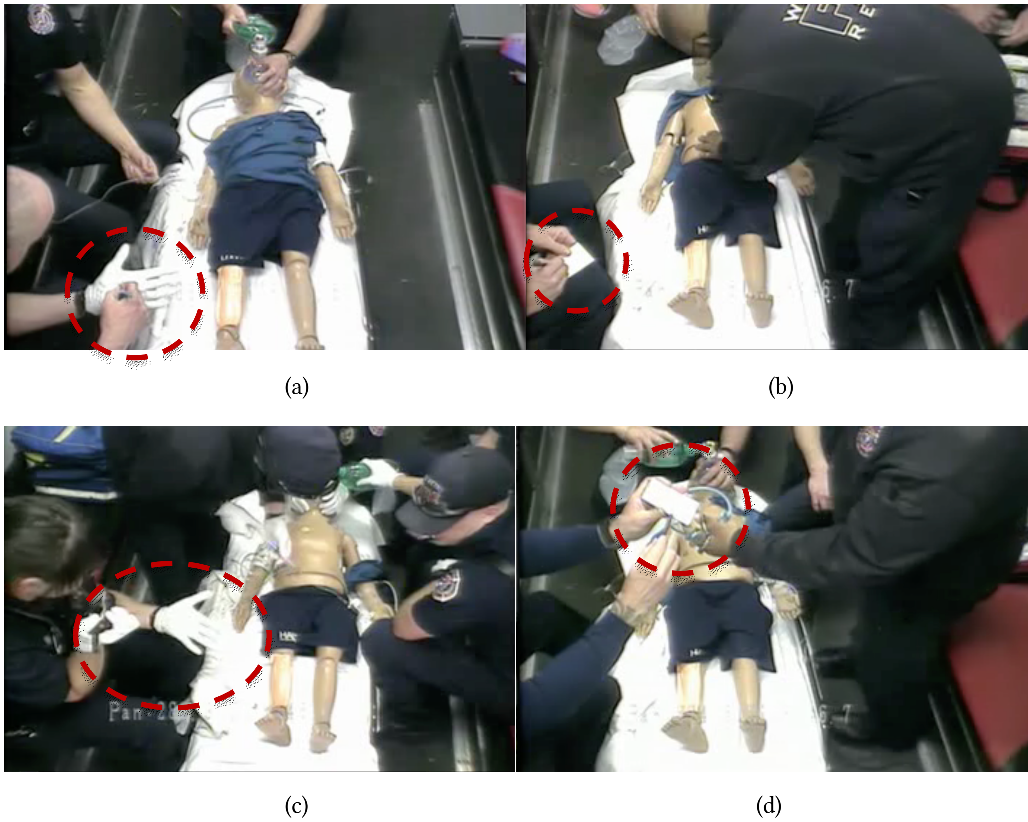

Figure 3: a) jotting down notes on a gloved hand, b) taking notes on a notepad, c) referring to notes while reporting to the hospital, d) sharing notes with other paramedics.

4.1.3 Artifacts. We found several artifacts in this setting were used as cognitive aids—prompts designed to help users complete a task or a series of tasks [57]—by EMS providers. A typical example is the vital signs monitor which is a medical tool for monitoring the patient's physiological status. We noticed that paramedics looked at the vital signs monitor from time to time to keep track of patient status. In particular, they would gaze at the monitor on occasion, such as after performing a treatment (i.e., to check if the treatment was effective). Another example of external cognitive aids is the paper-based or mobile medication chart, which was often used to determine the most appropriate medication dosage for the patient. This tool reduced paramedics' cognitive workload in remembering the correct medication dosage for patients with different age and weight.

We also found that team leaders sometimes took notes to preserve information. The commonly documented information types included patient demographics (e.g., age), mechanism of injury (e.g., how the patient got illness or what happened to the patient), and vital signs (e.g., blood pressure, respiratory rate). This work practice occurred in 16 out of 25 simulations. We found that team leaders neither used electronic documentation systems or paper records nor performed any formal documentation practice in the simulations. Instead, they used some "temporary" memory aids, such as hand glove (Figure 3a) or paper note (Figure 3b), to document patient data. Such documentation practice is related to the "creating scaffolding" concept of the DiCoT framework, that is, EMS providers created and used temporary artifacts to simplify their cognitive tasks (e.g., remembering critical patient information). The excerpt below (excerpt#1) illustrates the work practice of a team leader jotting down notes on his gloved hand with a pen.

#Excerpt 1

Speaker	Subject	Dialogue and Action
Team Leader	Patient Mother	How old is your boy?
Patient Mother	Team Leader	He is four. [*Team leader makes a note on his hand*]
Team Leader	Patient Mother	When did you last see him normal?
Patient Mother	Team Leader	Well I was getting in the shower about half an hour ago. [*Team leader makes a note on his hand*] I heard him in the kitchen and I thought he was just getting something to eat. And then I went out there and I noticed he was on the floor. But I think he was getting his medicine, because I found this bottle on the counter.
Team Leader	Patient Mother	What kind of medicine is it?
Patient Mother	Team Leader	He takes Clonidine.
Team Leader	Patient Mother	Clonidine? [*Team leader makes a note on his hand*]
Patient Mother	Team Leader	Yes. He has ADHD. [*Team leader makes a note on his hand*]
Team Leader	Patient Mother	Okay. And you found it (the bottle of Clonidine) open?
Patient Mother	Team Leader	Yeah, and it's liquid and it's all gone. There was a little bit on the counter, but it was mostly gone. [*Team leader makes a note on his hand*]

This finding is consistent with prior work that medical professionals often create temporary documents due to the lack of time for documentation or the difficulty accessing documentation tools [28-30, 32, 33]. Despite their informal nature, these artifacts serve as a means to support cognition by reducing the memory load of paramedics. For example, we found that team leaders often referred to the notes for further use, such as when 1) answering other team members' questions about the patient's details (e.g., age, medical history), 2) making treatment decisions (e.g., using patient's age to determine medication dosage), and 3) calling the hospital to relay information (Figure 3c). We also found a few instances where the scribbled notes serve as a "common artifact" [58] as they were shared between paramedics. For instance, in a simulation, a medication paramedic rather than the team leader was notifying the hospital. This paramedic first reported a few pieces of information such as the treatments and the most recent vital signs. But the reporting paramedic forgot to mention the mechanism (e.g., medicine overdose) and the patient's medical history (e.g., allergies and medical conditions). At this point, the team leader pointed to this information on his notepad to remind the medication paramedic to report these details as well (Figure 3d).

We also found that the pattern of using temporary artifacts varied among paramedics. Of the 16 simulations where temporary artifacts were used, only three paramedics used a notepad while the rest taking notes on their gloved hand. The frequency of using the temporary artifact in a simulation also varied, ranging between one time and seven times. These findings may signal that the use of memory aids is contingent on individual habits.

4.2 Challenges in the Information Acquisition and Decision Making during Pre-hospital Care

Even though each EMS team functions as a distributed cognition system, we observed several challenges in information acquisition and decision making during this fast-paced medical environment, including 1) lack of detailed documentation in real time, 2) situation recall issues, 3) situation awareness issues, 4) miscommunication and lack of closed-loop communication, 5) challenges in decision making, and 6) issues in pre-hospital communication. Below we describe each challenge in greater details.

4.2.1 Lack of Detailed Documentation. Documentation is a critical component of patient care that records the detailed and temporal account of treatments and patient status [59]. Usually hospital-based care teams have a dedicated role (e.g., scribe nurse) or dedicated time for the documentation tasks; for example, nurses or clinicians can spend a significant amount of time charting patient record using EHRs during and after clinical encounters. In our research setting, however, we observed the lack of detailed and formal documentation by paramedics in real time. First, despite note-taking that occurred in 16 out of 25 simulations, there was no formal documentation practice. That is, neither paper patient record nor electronic documentation system was used by paramedics to capture patient data in the field. They only scribbled notes on either their hand glove or notepad. This finding aligns with the prior work reporting that EMS practitioners often use temporary artifacts and informal documentation methods, despite the availability of EHRs [33]. These artifacts, however, are vulnerable to being torn, lost, or contaminated. Second, minimal information was recorded. Other than patient's demographics and vital signs, we rarely saw paramedics recording other types of information (e.g., dosage of administered medications and fluids and what medical procedures have been completed), even though they sometimes encountered issues in recalling such information, as we report in the following section.

Several factors may contribute to the lack of detailed and formal documentation. Unlike other clinical settings, the EMS team does not have a dedicated role (e.g., scribe nurse) for documentation. The task of recording information usually falls on the shoulder of team leaders. However, they had to perform hands-on examinations and treatments on patients from time to time while managing the entire team, communicating with the patient's parents, and integrating a significant amount of information coming from multiple sources in a short time period. As a result, EMS team leaders often experienced high physical and cognitive workload, limiting their capability for detailed information recording. Therefore, the hands- and eyes-busy EMS context poses significant challenges on real-time data capture and decision making.

4.2.2 Situation Recall Issues. Paramedics relied heavily on short-term memory to recall information when responding to inquiries. Consequently, we found 44 instances in 17 simulation sessions where paramedics could not quickly recall certain information, such as what had happened to the patient (e.g., the mechanism of injury), what had been done (e.g., the dosage of medications and fluids given to the patient), what was the patient status (e.g., vital signs before administering a medication), and what was the decision (e.g., the treatment decision made a moment ago). In particular, almost half of the observed situation-recall problems occurred to team leaders. When this happened, they usually asked for the information from other team members.

The following excerpt (excerpt#2) illustrates how paramedics encountered issues in recalling patient information. In this excerpt, the team leader asked for the patient's blood pressure, which was provide by one team member (PL1). The team leader wrote it down on his glove and then inquired about the heart rate and respiratory rate of the patient. About one minute later, the paramedic (PL1) who previously reported the respiratory rate asked for that information. Here we can see that PL1 encountered difficulty in recalling the information that was identified only a moment ago. Later, the team decided to administer normal saline to improve the patient's status. About three minutes after the fluid administration was started, the team leader asked the team to report any improvement over the patient's status (e.g., respiratory rate). PL1 reported the result (heart rate was improved) and suggested rechecking the blood pressure. The team leader then asked about the blood pressure before administering the fluid, which was reported a few minutes ago. This is another example of the situation recall issue. It is worth noting that the team leader jotted down the number when it was reported, but he did not check his note for the information; instead, he chose to make a verbal inquiry.

#Excerpt 2

Speaker	Subject	Dialogue and Action
Team Leader	Team	Can we get the blood pressure?
PL1	Team Leader	What we can see is 60/35.
Team Leader		60/35. [*Team leader makes notes on his glove*]
Team Leader	PL1	And what's her respiratory rate?
PL1	Team Leader	43.
[*About a minute later*]		
PL1	Team	What's her respiratory rate?
Team Leader	PL1	43 and we don't have breath sounds on her yet.
PH	Team Leader	We had breath sounds, and they were clear.
[*About three minutes after the fluid has been started, the following conversation occurs.*]		
Team Leader	Team	Okay, is there any change with her respiratory? Are we getting really good compliance?
PL1	Team Leader	Heart rate is starting to come down a little bit. I see it at one hundred. Let's go ahead and recycle blood pressure please.
Team Leader	PL1	What was the last pressure by the way?
PL1	Team Leader	60/35 I believe is what I saw.

4.2.3 Situation Awareness Issues. Situation awareness is defined as "*the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and projection of their status in the near future*" [60]. Awareness of individual and group activities is critical to successful collaboration. In care delivery, providers need to maintain awareness of their tasks, team activities, patient status, and the care process [61, 62].

Like other high-stake medical settings [62-64], we found that paramedics also relied heavily on verbal communication to maintain awareness during pre-hospital care process. We also observed team leaders often summarizing the tasks that had been performed so that everyone was on the same page. Despite so, we still observed the occurrence of problems in maintaining situation awareness (n=56, occurred in 19 simulations). That is, paramedics sometimes lacked knowledge of the tasks that other paramedics had already carried out, such as the administration of medication and fluids. It is more evident when the paramedics did not verbally report the task they were performing, and thus, other team members, including the team leader, may not be aware of the completion of the task. This issue could lead to repeated questions and even affect efficient team collaboration and decision making. For example, as shown in the following excerpt (excerpt#3), while the team leader was talking to the patient's mother to learn details about the patient, one paramedic (PL1) started preparing the fluids and getting IV access on the patient (without the instruction from the team leader). When the fluid bag was set up, PL1 did not verbally report its readiness. About half a minute later, the patient's blood pressure was dropping, but the team leader was not aware of this situation. PR1, who was managing medications, noticed it and reported to the team leader. After confirming the vital stats with PR1, the team leader asked if the IV fluid was started. In this example, we can see that as the team leader was busy with other tasks, he could not effectively maintain awareness of on-going tasks and patient status. Fortunately, as the EMS team functions as a distributed cognition system, other members noticed the issue and alerted the entire team.

#Excerpt 3

Speaker	Subject	Dialogue and Action
[*Team leader is talking to the patient's parent while another paramedic (PL1) is preparing the IV fluid.*]		
[*A moment later, the IV fluid is ready to administer but PL1 didn't announce it.*]		
PR1	Team Leader	So his BP is pretty low right now.
Team Leader	PR1	What is it?
PR1	Team Leader	It's 55 over 28.
Team Leader	Team	It's quite low. Where is our IV? It started yet?

Our analysis also showed that paramedics lacked awareness of mutual information needs, resulting in inefficient information flow and collaboration. We used the concept of "anticipation ratio" [65]–the ratio of the number of communications providing information to the number of communications requesting information–to measure the extent to which paramedics were aware of each other's information needs. A greater than one (>1.0) anticipation ratio indicates that team members are anticipating the information needs of others and are proactively "pushing" information towards those need the information. In contrast, a less than one (<1.0) ratio suggests low awareness of mutual information needs among team members, requiring them to actively request or "pull" information from each other [65]. By analyzing the number of inquiries and reporting instances in 25 simulations, we identified an average anticipation ratio of 0.49 (range: 0.21-0.84, SD: 0.21), suggesting that paramedics were poorly anticipating each other's information needs. This issue could lead to repeated questions, affecting communication efficiency in the field. This observation can be exemplified by excerpt#3: PL1 had little anticipation of the team leader's need to know the fluid administration, so he did not verbally report this task. This lack of communication led to situational awareness issues.

4.2.4 Miscommunication and Lack of Closed-Loop Communication. Similar to other fast-paced, dynamic medical settings, we observed many instances of miscommunication. One primary cause of miscommunication is the ambient noise, such as cross-talking, hindering the clear information exchange between paramedics. As shown in the following excerpt (excerpt#4), the patient started shaking due to seizure, so the team leader (TL) directed the medication-paramedics (PL1) to start administering fluids immediately. TL asked PL1 about what type of fluid they were preparing (IV vs. IO) while using a smartphone-based medication application to calculate the dosage. But at this moment, PL1 was discussing with PR1, another paramedic who was preparing fluid bag and syringe, on the dosage and type of fluid to give. Apparently, they did not hear the question so TL had to ask the same question again.

Our analysis also revealed another salient issue—lack of closed-loop communication—which often resulted in inefficient information flow and situation awareness. A typical example of this issue is that a paramedic who asked about patient status received no response from other members. For instance, in one scenario, we observed the medication paramedic asked: "*Can somebody get a BP (blood pressure)?*" Since this inquiry was not directed to a specific person, he did not get a response. Our quantitative data confirmed our observation as about 17.6% of inquiries (149 out of 854) went unanswered.

#Excerpt 4

Speaker	Subject	Dialogue and Action
[*Team leader is talking to the patient's mother. At this moment, the patient starts shaking due to seizure and the patient's mother is panicking*.]		
[*Team leader directs the medication paramedics to administer fluids immediately while using a smartphone application to determine the fluid dosage*.]		
Team Leader	PL1	IV or IO?
PL1	PR1	We are going to go with one milligram per milliliter.
PR1	PL1	Let's go with IM (intramuscular injection) for now.
PL1	PR1	Okay.
Team Leader	PL1	IV or IO?
PL1	Team Leader	IV or IO? Nope. He said IM.
Team Leader	PL1	IM?
PL1	Team Leader	Yeah. The pink one. [*PL1 points to a specific section of the smartphone medication application*].

4.2.5 Challenges in Real-Time Decision Making. In total, we observed 76 individual decision-making and 149 group decision-making instances. This observation reveals that unlike some other medical teams where team leaders (e.g., physicians in charge) made all decisions and rarely consulted others [66, 67], the EMS team has more collaborative problem-solving activities. For instance, we found that the supervisory team members frequently discussed patient examination findings, vital signs, and symptoms with other paramedics to collectively make a decision that everybody agreed upon.

However, we did observe challenges in real-time decision making. For example, paramedics might not be able to recognize the need to perform the required treatments. Simulated scenarios in this study (e.g., hypovolemic shock) required the EMS team to perform timely interventions, such as administering IV fluid. To make this decision, paramedics must first recognize the patient is in shock, which is usually indicated by the vital signs and the patient's condition. However, we observed that paramedics sometimes had delays in obtaining vital signs or even missed taking a blood pressure that would had alerted them the patient was in shock. We also found that paramedics sometimes struggled to find and use the correct equipment; for instance, they used adult equipment on the pediatric patient in several simulation sessions.

4.2.6 Issues in Pre-Hospital Communication. In addition to stabilizing the patient, another essential task for paramedics is calling the hospital to give a verbal summary of the patient's condition and the care administered en route [5]. Timely and accurate communication between EMS teams in the field and hospital teams (also known as *pre-hospital communication*) is of utmost importance. However, prior work points out that this communication practice is always challenging [3, 68]. Based on our analysis, we found specific issues that lead to challenges in pre-hospital communication. First, the paramedics who reported to the hospital sometimes had difficulties in recalling specific information. This issue is related to the lack of documentation during the care process; since some situational information was not captured and properly recorded, the team leader often missed or could not remember the exact information when reporting to the hospital. Second, it is not always the same paramedic that gathered the information to communicate with the hospital. For instance, in one simulation, the team leader carried out data gathering but the verbal report to the hospital was performed by another paramedic. Lastly, the verbal report was conducted via radio and very brief. The lack of contextual information in the verbal report makes it difficult for hospital teams to anticipate the patient's needs [3]. We also noticed that the patient status might change drastically and new medications could be administered after the verbal report. However, such information was not shared with the hospital at all since EMS providers only communicated with the hospital once.

5 DISCUSSION

In this section, we first outline how the DiCoT framework helped us understand the way through which cognition is distributed in the EMS system. Then we describe the implications of our study, including 1) technology opportunities for supporting real-time data collection and integration, situation awareness, and decision making in dynamic medical settings, and 2) training opportunities for improving EMS teamwork and communication.

5.1 Distributed Cognition in the EMS Social-Technical System

The codified principles of the DiCoT framework guided us to look at whether cognition was distributed in the EMS system. The findings of this study show that cognition is indeed distributed across paramedics, artifacts/medical equipment, and physical environment in EMS. The physical layout model showed how the spatial arrangement of EMS crews influenced their horizon of observation, situation awareness, and access to artifacts. The information flow model allowed us to identify the information hub and understand how the information moves around the system. This model also helped us examine the existing challenges in information flow (e.g., miscommunication or lack of closed-loop communication, situation recall issues). Lastly, the artifacts model showed the important roles of medical equipment (e.g., vital signs monitor) and temporary artifacts (e.g., gloves and notepad) in supporting distributed cognition. By considering artifacts in the analysis, we also noticed issues in real-time documentation in the field, such as the lack of formal and detailed documentation.

The DiCoT framework has another model, called "Social Structures", which emphasizes how the social structures of a team or an organization map onto the goal structures of the system and how work is shared between different professionals. We did not explicitly apply this model in the study because we did not conduct interviews to collect data related to team hierarchy and social relationship (this is a limitation of this study as we describe later). Nevertheless, a typical ambulance unit is staffed by providers (e.g., two paramedics) who have same occupation and similar training. In the field, they self-organize their work towards the same goal (i.e., stabilizing the patient), even though a more experienced EMS professional may implicitly take the role of "team leader", similar to what was reported about other self-organizing teams [51]. In this regard, what is interesting is how the lack of clear division of labor would influence how the work is shared and coordinated. In our study, we observed that since all participants have undertaken similar training, they can monitor each other's work for "error checking" and offer help or even take over their co-worker's task if necessary. This self-organizing team nature enables effective functioning of EMS teams under extreme time pressure. However, we did observe drawbacks due to self-organizing; for instance, they could self-assign tasks and decide what to do without communicating with their co-workers, leading to situation awareness issues and miscommunication.

Overall, these results highlight the usefulness of DiCoT and its principles in helping researchers understand the basic mechanics of a socio-technical system. To the best of our knowledge, this is the first study using DiCoT to investigate EMS teamwork. We hope this study could contribute to the effort of bringing the DiCoT framework to a broader audience.

5.2 Implications for Technology Design

5.2.1 Enabling Rapid Data Collection in Real Time. As EMS teams do not have a designated scribe person for data work, we found that team leaders often took the responsibility of collecting, integrating, and documenting data. However, due to the fast work pace, it was never easy for team leaders to document detailed patient data using electronic documentation system. As such, we observed that paramedics or team leaders sometimes jotted down notes on scrap paper, notepads, or gloves to remember and recall certain information. This work practice is not uncommon in fast-paced medical work—care providers create and use temporary artifacts to work around issues in recording information and enable flexible modes of operation [24]. However, such informal documentary practice has many drawbacks. First, these temporary artifacts are easily getting torn, lost, or contaminated. Second, the physical handling of handheld artifacts could increase the likelihood of cross-contamination and patient infections, and consequently, affecting patient outcomes. Third, these temporary artifacts have limitation in recording accurate and detailed descriptions of the sequence of medical events [33], leading to challenges in situational information recall, decision making, and verbal communication with the receiving hospital. Also, the temporary artifacts are not considered formal documentation, and thus, paramedics still need to spend a significant amount of time after patient transport to complete the electronic medical record to fulfill the legal requirement. However, it is not only time-consuming but also that EMS providers may not be able to correctly recall all the essential details. Lastly, using paper-based or temporary artifacts may lead to inevitable poor handwriting, hindering real-time information processing to support situation awareness and communication during time- and safety-critical work settings [24].

These challenges highlight the necessity of providing appropriate technology support for real-time digitization of patient care activities during pre-hospital care [69]. HCI and CSCW researchers have paid considerable attention to patient data collection in a range of medical settings [32, 70-77]. Of interest here are related studies that focus on the use of EHR systems during patient encounters. These studies have shown that EHRs play an essential role in supporting information sharing and situation awareness in medical work [70, 72, 78]. However, the introduction of EHRs has also made the documentation of patient information more complicated because of the gaps between the actual clinicians' workflows and EHR design [36, 71, 79, 80]. For example, EHR systems force adherence to specific procedures and workflows that are not always feasible in practice, leading to adverse effects on clinicians' workflows [71, 75]. Also, electronic documentation is perceived cumbersome as it requires more time and cognitive resources to navigate information across screens [6, 81, 82]. The challenge in using handheld electronic documentation systems is exacerbated in EMS work, since the EMS team does not have a dedicated role for documentation. As we observed, EMS team leaders' eyes and hands are often occupied with patient assessment and treatment, limiting their abilities to hand carry a computer, interact with information on its screen, and use a pen for making inputs.

The unique characteristics of the EMS team call upon new modes of interaction with computing devices for data collection. Wireless biomonitoring systems with sensors have been proposed to continuously measure and record the vital parameters of the patient in the field [83, 84]. These systems are particularly useful in massive casualty incidents (MCI) or disaster scenarios because they can immediately detect and alert a deterioration in health status, allowing EMS providers to make triage decisions based on the measured physiological values. Despite their advantage in auto collection of vital signs, EMS providers still needed to use a separate handheld device (e.g., a tablet) to manually record other types of patient data (e.g., injury, treatment, symptoms, and neurological status), which still imposed a physical burden on them. Another technology solution for data capture is digital pen-based device. The digital pen is an ordinary ink pen with digital camera that digitally records the writing actions of the user by recognizing an almost invisible nonrepeating dot pattern that is printed on the paper. A number of studies have evaluated the feasibility of using the digital pen and paper technology to digitize patient data collection in clinical settings (e.g., [85-87]). The advantage of this technology is obvious, that is, allowing care providers to continue working with a familiar environment using pen and paper without any disruption to their current workflow. However, its accuracy is not optimal, especially in fast-paced environments [88].

In recent years, smart glasses (e.g., head-mounted, wearable devices with a transparent screen and a video camera that can capture visual data) have been evaluated to determine their ability of supporting data capture and integration in real time [69, 89, 90]. They offer novel interaction techniques, such as hands-free operation and context-aware user interaction [91, 92], which can minimize clinicians' active interaction with the systems and thus, making the smart glasses better coexist with the clinical workflows [93]. For example, to improve wound care management, Aldaz, et al. [94] developed a smart glass application to enable hands-free digital image capture and transfer to a patient's EHR record through gestural and voice commands. Although studies have examined the use of smart glasses for both in-patient and remote medical procedures in hospital-based clinical settings [95-99], how they can support fast-paced and noisy medical work during out-of-hospital encounters remains unanswered. Future research can examine how fast-response teams with limited time and cognitive resources might use wearable technologies (such as smart glasses) to capture and integrate patient data in a hands-free manner.

Lastly, we observed individual differences in using temporary artifacts for data capture. That is, some paramedics preferred using a notepad while the rest preferred jotting down notes on their gloved hand. In addition, their documentation frequency in the field was also different. These differences need to be taken into consideration when designing technology support to meet individual care provider's needs. Considering the cost of system maintenance and the importance of system integration, it might not be realistic to provide individualized technology solution for paramedics in the same EMS agency. But future work should look into the pattern of technology use by EMS providers as they may use the same technology in different ways [100].

5.2.2 Enhancing Situational Awareness and Decision Making in Dynamic Medical Settings. We observed a considerable number of issues related to situation awareness. For example, team leaders sometimes lacked knowledge of the tasks that had already been carried out or medication that had been administered by other paramedics. We also observed that it is not always the same paramedic (e.g., team leader) reporting patient information to the receiving hospital. Therefore, it is necessary for other team members to maintain an awareness of patient status and team activities in case they need to make the verbal report. These findings highlight the importance of designing and developing technical systems to support situation awareness in the field. The technology for situation awareness support needs to capture, manage, and distribute situational information, requiring a medical professional (e.g., a scribe nurse) to manage the technology or provide input. However, as discussed in the preceding section, this task is very challenging for EMS teams since there is no such role in data work. In addition, the velocity of information to be captured and maintained in the field is very high, posing burdens on EMS providers' cognitive process. It might be useful to leverage sensing technologies such as radio-frequency identification (RFID) to automatically recognize and capture medical activities (e.g., administration of medication). Prior work has demonstrated the feasibility of using RFID along with other sensing technologies to identify cues for recognizing activities and use of objects in a crowded and fast-paced medical setting [101]. To distribute situational information to the entire EMS team, one option is through shared information displays installed inside the ambulance [102]. Such displays have been used to present contextual information to augment work coordination and situation awareness in various dynamic medical domains, including critical care units [103], operating rooms [64], emergency departments [104], and trauma resuscitation [4]. Future work can examine the feasibility of implementing and deploying shared information displays inside the ambulance (e.g., where to install, and the size and orientation of the display).

Our analysis also revealed the challenges faced by paramedics in making timely and accurate decisions. For example, they may not be able to recognize the symptoms of a specific illness or the needs of performing the required treatments. They also have difficulties in managing pediatric patients. One primary reason for these challenges is that paramedics usually do not receive extensive medical training as their counterparts (e.g., physicians) do. Therefore, they sometimes lack experience and adequate knowledge to manage critical and complicated patient cases, demanding effective decision support. A possible solution is medical checklists, which have been widely used as cognitive aids to guide a range of complex patient care activities and ensure compliance with protocols [105-107]. We believe EMS team can benefit from medical checklists given their challenges in managing certain types of patients [108]. For example, the checklist can suggest the correct equipment and medical procedures for treating pediatric patients who present symptoms of, i.e., seizure or medicine overdose. The design of the EMS checklists needs to account for the unique characteristics of pre-hospital care. That is, pre-hospital care is often characterized as messy and unpredictable. The checklist, therefore, cannot be static and linear—a limitation that often leads to ineffectiveness in patient care, and low adoption and compliance rates [109, 110]. Instead, the EMS checklists need to be dynamic and flexible enough to cover not only frequent activities but also less frequent but critical tasks, allowing for adaptability to different patient scenarios and changing environment.

Some studies in emergency responses have developed digital cognitive aids for EMS teams [24-26]. Despite so, some key challenges for developing effective decision support for EMS teams have not been successfully addressed, including obstacles in timely information integration and acquisition, usability issues, cognitive burden of using the system, and impacts on patient interaction and teamwork. Future work should focus on what technology form and mode of interaction can address those limitations.

5.2.3 Facilitating Information Sharing and Care Coordination Between EMS and ED Teams. Management of critically-ill patients in diverse field settings (e.g., rural areas, wilderness) requires timely and responsive care coordination between EMS and ED teams [38]. For example, the treatment of a pediatric patient with traumatic brain injury with a rapidly changing state of consciousness often requires a considerate level of knowledge and skills that EMS providers may not have. When a complicated patient case presents, EMS providers may need to consult with a more experienced ED physician regarding treatment plan, likely diagnoses, and even how to perform some advanced medical procedures that are critical to saving patients' lives during ambulance transport [38, 111-115]. However, care coordination and communication between pre-hospital EMS and hospital ED teams remain ineffective and challenging [68, 116, 117]. Unlike collocated teams which can rely on a range of coordination mechanisms (e.g., tacit monitoring, visual cues) to facilitate their work [48, 49, 63], EMS teams can only rely on radios or cellular links, a traditional mechanism that has been used since 1990s, to communicate with the hospital. Although cellular radio has benefits that lead to its persistent use in healthcare settings, it has intrinsic limitations such as limiting the accuracy and efficiency of describing the situation and patient status [118]. This limitation makes the EMS verbal report very brief and lack essential details. On the other side, ED physicians at the hospital have difficulties understanding what is precisely happening in the field and the signs of the patient [5]. These limitations of current mechanisms inevitably lead to confusion and miscommunication, creating challenges in establishing common understandings between EMS teams in the field and ED teams at the receiving hospital [3]. Literature calls for a more effective approach to facilitate information sharing between distributed EMS and ED teams [119].

Over the past two decades, many research efforts have been devoted to developing ambulance-based telemedicine systems (e.g., [114, 120-126]) to support EMS-ED care coordination. This type of technology is integrated into ambulances and uses mobile networks to enable EMS providers in the field to access experts at the receiving hospital through real-time, audio-video communication. Despite the benefits, these systems have not been adequately adopted due in part to their specific limitations, such as portability and usability issues [120, 126, 127]. For example, EMS providers are mobile as they provide urgent care to patients, therefore, it is almost impossible for them to use ambulance-based telemedicine devices outside of the ambulance where a significant portion of patient care occurs [120]. Even inside the ambulance, using telemedicine devices is also challenging due to fixed placement of the equipment; for instance, EMS providers may need to maneuver the camera and speaker for better information relay [126].

With the motivation to address the limitations of ambulance-based telemedicine technology, several mobile- or tablet-based visual systems for pre-hospital communication were developed and tested [7, 115, 128-131]. These visual technologies provide a portable solution for EMS providers to share text, still images, and video clips with ED physicians. If needed, they can also have direct video conversation with ED physicians to better explain the patient situation and receive medical guidance. Another visual technology that has been gaining momentum is the smart glass applications, which can serve as an unobtrusive technological conduit between pre-hospital and hospital care providers. For example, they can be used to capture contextual information in the field (e.g., photos and videos) and share them with hospital teams to support their understanding of the patient's conditions. Also, the novel interaction techniques afforded by smart glasses, such as Augmented Reality (AR) and remote hand gesturing, allow for seamless care coordination and consultations at a distance [132, 133]. Several studies have demonstrated that smart glasses are useful in supporting care management [92, 132, 134-137] and can enable secure, Health Insurance Portability and Accountability Act (HIPAA) compliant communications [138]. Thus, using smart glasses to support information sharing and care coordination between the field and hospital is a feasible approach.

To ensure the adoption of such advanced visual-based systems, several design considerations should be taken into account. First, a common problem of video-based communication is that it might be difficult for the sender to establish what visual information is shared and for the receiver on the other side to capture the full array of visual cues [139]. Studies on smart glasses have reported this problem—there is a mismatch between what the onsite care provider and the tele-consultant can see due to the range of the camera and the direction of gaze [140, 141]. Second, technical limitations are a major barrier of successful use of visual-based systems between distributed medical teams, including unstable connections to mobile network [142] and difficulties in transmitting clear audios and high-resolution videos [96, 115, 130]. With the rapid development of 5G technology and the proposition of building a dedicated broadband network for first responders (e.g., First-Net[4]), it is anticipated that those technical barriers can be addressed in the near future. Third, prior studies on visual-based pre-hospital communication systems primarily focused on technical aspects, with few attentions paid to usability and human factors. Since usability issues could affect the efficient use of technologies in the pre-hospital setting, they should receive equal attention as technical challenges [119]. In particular, researchers and designers should pay close attention to the cognitive and physical stressors of EMS providers who need to deal with critical patients and perform multiple tasks simultaneously. The hands- and eyes-busy nature of pre-hospital care pose challenges in using computing devices. For example, one study reported that difficulties could arise from touching accidentally or working with dirty

[4] FirstNet. https://firstnet.gov/about

hands because users tended not to touch their device when their hands are not clean or with blood [24]. Another study reported that when wearing a wearable communication device, sudden head movements by EMS providers could cause issues in generating stable visualization for remote tele-consultants [142]. Lastly, literature has highlighted the importance of integrating systems into the workflow of emergency care providers [68, 119]. Failing to account for existing workflow could lead to unintended consequences, such as increased workload or limited system use in real time [26]. Future work should look into whether introducing visual-based technologies could change the job requirements and work practices of EMS and ED providers.

5.2.4 Integrating Technology Supports. EMS remains one of few medical domains that have limited technology support. As described in the preceding sections, there are several technology opportunities to support different aspects of EMS work, including data collection and integration, decision making, situation awareness, and communication. The technology types range from handheld data collection tools to wearable devices. However, given the hands- and eyes-busy nature of EMS, the technology supports for EMS should be as unobtrusive and minimal as possible. Thus, we suggest that system designers and researchers should think about how to integrate different types of technology supports into one interoperable platform. For example, the checklist can be digitized by integrating into an existing data collection system (e.g., EHR) or a new digital tool (e.g., smart glasses) to reduce the needs of managing multiple devices and artifacts. In addition, ensuring seamless information flow across different devices is also crucial. Researchers have examined different approaches and strategies to achieve such goals. For example, the openEHR infrastructure has been piloted in many countries to standardize data operation and ensure universal (and even international) interoperability among all forms of electronic data [143]. Despite reported success from several research projects [144, 145], further research is called upon by CSCW researchers to investigate social-technical issues associated with implementing and scaling the openEHR infrastructure [78, 146].

5.3 Implications for EMS Training

Communication is a critical aspect of emergency care and teamwork [53, 147-149]. Similar to prior work [149], we found that verbal communication was the major vehicle for sharing information and facilitating the division of cognitive labor. Even though our participants had undertaken training modules on closed-loop communication, we still found many instances where paramedics miscommunicated or closed-loop communication was not used, posing challenges in teamwork and maintaining situational awareness. We also observed the lack of mutual awareness of information needs among paramedics. These challenges aligned with previous work showing that unstructured communication was the leading factor of communication errors [148]. Thus, further training on communication and teamwork would be beneficial. Educators and managers of EMS teams should include core principles and concepts of team communication, which are standard curriculum for hospital-based teams, in their training curriculum, and continue investigating strategies and mechanisms to improve communication among paramedics. In addition, more contextualized simulation-based trainings are needed [150-152]. That is, simulations should include the complicating characteristics of pre-hospital care to help EMS practitioners 1) practice patient care skills, 2) manage barriers in communication and teamwork, and 3) test critical situations that can be challenging to conduct in real emergencies. When designing such contextualized simulations and training environment, it is important to involve both end-users (e.g., EMS and ED providers) and other stakeholders during the whole design process [151].

5.4 Limitations

Several limitations of this study should be noted. First, we solely relied on video review to investigate data work and decision making in emergency medical services, which may not allow us to capture a comprehensive view of EMS work practices. For example, some activities may have occurred outside the visual field of the cameras and video recordings may not have captured all verbal communication and non-verbal cues clearly. Also, simulations cannot speak to care delivered outside of an ambulance. We will conduct field studies, including interviews and *in situ* observation, to confirm our findings and elicit additional insights (e.g., the impact of EMS social structures and team hierarchy on work distribution and collaboration). Despite this limitation, it is worth noting that video analysis allowed us to analyze the data offline and capture fine-grained, essential details of fast-paced EMS work, which are otherwise challenging to study in real-world settings. Second, there may exist reviewer bias in the observations. To limit this bias, two reviewers coded the video data independently and their analyses were discussed as a group until reaching consensus. Third, we did not pay close attention to medical errors or patient safety issues. Future work can look into how the issues in data collection and teamwork contribute to adverse patient outcomes.

6 CONCLUSION

In this study, we reviewed 25 simulation videos to examine information acquisition and decision-making in emergency medical services. Based on the DiCoT framework, our qualitative and quantitative analyses showed that EMS teams relied on verbal communication, non-verbal cues, and cognitive aids to distribute the cognitive labor and maintain the working memory. Several challenges in information acquisition and decision making were also noted. Lastly, we discussed the implications of this study to theoretical development of DiCoT, technology opportunities for supporting dynamic EMS teamwork, and EMS training. Our continuing efforts include conducting field studies to derive system requirements for novel technologies that can reduce the physical and cognitive load of using computing devices by emergency care professionals.

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