Transactive Memory in Trauma Resuscitation

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ABSTRACT
This paper describes an ethnographic study conducted to explore the possibilities for future design and development of technological support for trauma teams. We videotaped 10 trauma resuscitations and transcribed each event. Using a framework that we developed, we coded each transcript to allow qualitative and quantitative analysis of the trauma teams' collaborative processes. We analyzed teams' tasks, interactions, and communication patterns that support information acquisition and sharing. Our results showed the importance of team transactive memory, but also pointed to inefficiencies in communication processes, which enable the functioning of this collective memory system. Based on quantitative and qualitative observations of trauma teamwork, we present opportunities for technological solutions that may reduce the cognitive effort needed for maintaining the working memory of trauma teams.

Author Keywords
Teamwork, communication, transactive memory, cognitive work analysis, distributed cognition, healthcare, trauma.

ACM Classification Keywords
H.5.3 [Group and Organization Interfaces]: Computer-supported cooperative work; H.1.2 [User/Machine Systems]: Human information processing.

INTRODUCTION

Despite advances in pre-hospital and hospital-based care, trauma remains a leading cause of death that disproportionately affects children and young adults [21]. While training and standardization have been used to improve team performance, errors and inefficiencies persist even among experienced teams [9]. Unlike other high-risk domains, such as traffic control rooms or airplane cockpits, where team members utilize sensors or computerized controls to accomplish their specific goals [11,13], trauma resuscitation operates with few devices for tracking patient status or team activities. In current practice, it mostly relies on highly inter-dependent teamwork, verbal communication, and the judgment and experience of trauma team members. These unique features of trauma teamwork often result in failures in team communication and difficulties in acquiring information needed for decision-making. A study of communication in trauma resuscitation [3] found that almost 50% of attempted verbal communication was inaudible and >50% did not lead to effective action. Initial efforts to use decision support technologies in trauma care have been promising but have shown limited usability in clinical practice [4,7,8]. To date, it is not known whether computer aids for trauma resuscitation should support certain individuals, the overall team, or both, and in what form. We believe that uncovering work patterns and information flow in trauma teams will help address these issues.

Collaborative team activities in healthcare have been studied widely in "workplace studies" [10]. Through detailed analyses of tacit work practices and procedures, these studies have mostly focused on the social and interactional character of organizational activities in operating rooms, anesthesia, and hospital wards [2,12,16, 22]. Despite this tradition of research on teamwork in time- and safety-critical work settings within CSCW community, trauma resuscitation remains relatively understudied. While some commonalities exist between trauma care, anesthesia and surgery, trauma teams exhibit several unique features not yet studied from a CSCW perspective. The work-place studies have typically adopted ethnomethodology as their primary method, relying on repeated scrutiny of video recordings for analyzing verbal and nonverbal interactions. While effective in explicating teamwork practices, we found this approach impractical for studying trauma resuscitation given the difficulty of acquiring access to this domain and inability to use video recordings for extended period. Even so, there have been a few studies [19,20] of information flow in multidisciplinary teams in acute healthcare settings, focusing on teams in small, rural hospitals, with dynamics different than trauma teams.

In this paper, we examine the work processes of trauma teams in a trauma center of an urban, teaching hospital. We specifically focus on teams' verbal communication, information acquisition, storage, and retrieval. We use transactive memory theory [24] to argue that trauma teams function as transactive memory systems in which team leaders and decision-makers mostly rely on collective memory to acquire, store, and recall relevant information. While it has been shown that group memory can lead to

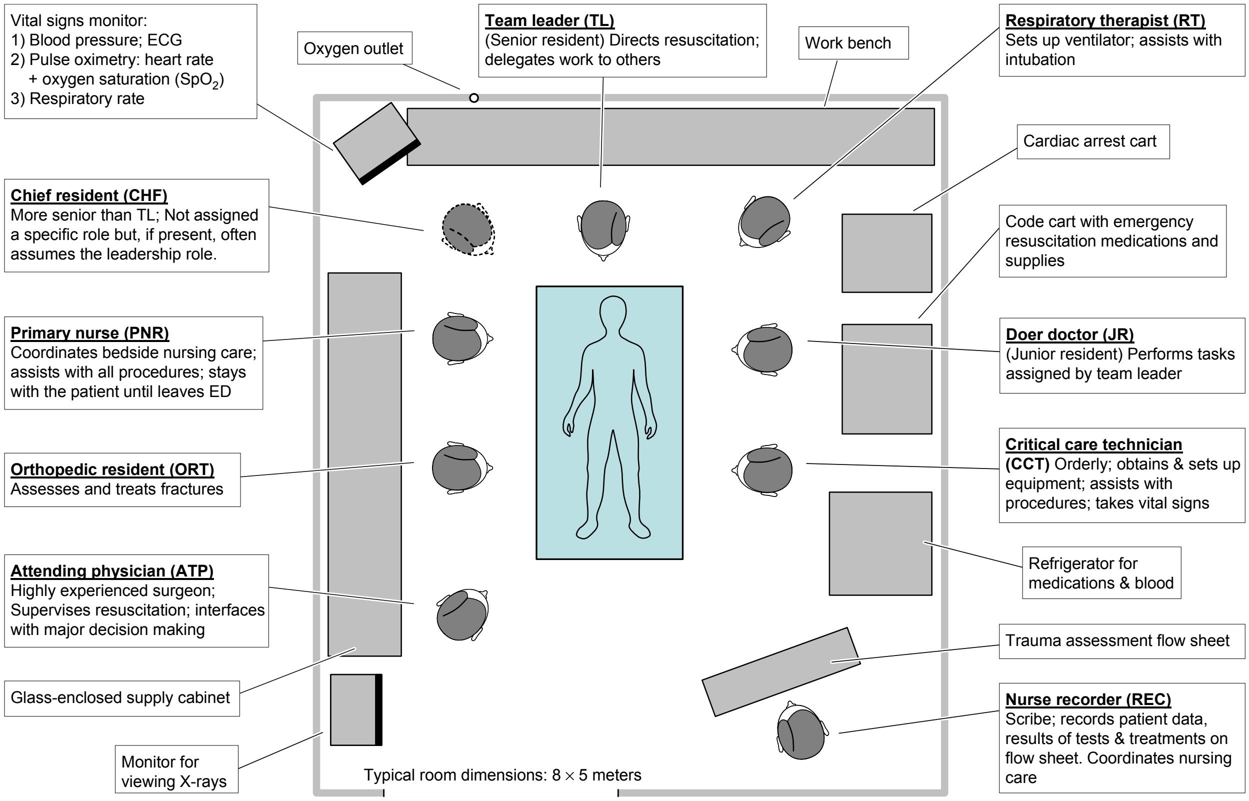

Figure 1. Emergency department (ED) trauma bay: typical actors and artifacts in a trauma resuscitation event.

superior task performance [17], our observations imply that reliance on collective memory often caused inefficiencies during trauma resuscitation. This observation highlights the need for improving trauma teams' performance by developing technological solutions that aid the use of collective memory and other work processes.

BACKGROUND AND RELATED WORK

Trauma Resuscitation Overview

The purpose of trauma resuscitation is to identify and immediately treat life-threatening injuries. The team's goal is to stabilize the patient, determine the extent of the injury and develop a treatment plan to be carried out during hospitalization. To accomplish these goals, trauma teams follow a well-defined protocol called Advanced Trauma Life Support (ATLS) [1]. The first phase of ATLS is a rapid evaluation to find life-threatening injuries (primary survey). These steps include evaluation and treatment of airway injuries (*Airway* [A]), followed by evaluation of the respiratory system (*Breathing* [B]) and blood circulation (*Circulation* [C]), and finally by a neurological assessment (*Disability* [D]). This initial phase is then followed by the secondary survey, a detailed assessment to identify other injuries. These steps are often repeated to monitor changes in patient status and the impact of treatments.

Trauma teams are multidisciplinary and comprise medical personnel with training in the management of critically injured patients. The team structure in most trauma centers is similar to that of our center (Figure 1). The EMS paramedics transporting the patient alert the emergency department (ED) of their initial assessment and pending time of arrival. Upon receiving this alert, members of the trauma team assemble in a designated room ("trauma bay") in the ED. While a core team is present through the entire effort, some workers may leave and return, and additional specialists may join after the evaluation has started. The number of team members may be as high as 15 depending on ED staffing, time of day, and severity of the injury.

The roles and responsibilities of the team members are precisely defined to avoid redundancy and ensure completion of needed tasks. Team activities are coordinated mostly verbally. The team leader (usually a senior resident, TL) mainly directs team activities and avoids getting involved in procedures. A chief resident (CHF), with more years of training than the team leader, may also be present. The chief resident provides additional oversight and supervision for the team leader, when present. The leadership role may change between residents (TL and CHF) and attending surgeons (ATP) depending on the changing patient condition and skills of the individuals involved [15]. The team leader is assisted by a junior resident (JR) who performs hands-on evaluation and treatment. An anesthesiologist (ANST) and respiratory therapist (RT) are available to assist with management of the airway injuries, while orthopedic surgeon (ORT) manages orthopedic injuries. One nurse is dedicated primarily to the patient care (the primary nurse, PNR) and is aided by a second nurse (the recorder, REC) who documents the event. A critical care technician (CCT) performs routine tasks, such as blood pressure measurement, and provides needed equipment and supplies. Other members of the team include a pharmacist who dispenses medications on-site and an x-ray technician available for obtaining radiographs.

Current technologies in trauma bay include: a) trauma pagers for initial alerting of team members; b) a paper-based trauma flow sheet for documenting patient data and treatments; c) a vital signs monitor for displaying patient's vital signs; d) a digital x-ray workstation for viewing x-ray images; e) diagnostic tools for conducting various tests (e.g., HemoCue for blood analysis); f) wall charts for displaying information on treatment parameters by patient age/weight; and, g) a whiteboard outside the room that is used for recording patient information before arrival.

Related Work

Due to the importance and frequency of decision-making errors in trauma resuscitation, prior technologies have mainly focused on providing computerized clinical decision support. An example is TraumAid [8], an artificial intelligence system that uses expert rules and logical deduction to generate management goals for trauma resuscitation. The design of this system was primarily based on interviewing experts to extract rules used in decision-making. When used in 40 actual trauma resuscitations, physicians found the system helpful in 21 interactions (53%), serving mainly to reassure the physicians of their plans [4]. A major disadvantage of this system was that it required additional work and time from physicians because data entry was manual and results were available only as text on a computer screen.

Despite considerable efforts, few decision support systems have been developed that are actually used in clinical practice [7]. Reasons that are usually cited include the challenge of automatically acquiring information from diverse sources in a dynamic environment, the difficulty of synthesizing acquired information into meaningful output and recommendations, worker resistance to unproven techno-logy, and the stringent need for a fail-safe system.

Transactive Memory Theory

Transactive memory refers to the specialized division of labor for handling information used by groups [24]. As group members acquire specific roles and responsibilities, each individual learns and memorizes information from his or her specialty, as well as meta-information about who in the group remembers what. To encode, store, and retrieve information from individual memory systems, group members perform "transactions" or communications, which makes this collective memory system "transactive." Such specialization and delegation reduces the cognitive load of each individual while enabling access to a larger pool of information across domains.

The concept of transactive memory has been used widely in modeling the functioning of working teams [18]. Members of trauma teams sometimes may not know each other by name, but even then, they are familiar with the responsibilities of all roles. Roles can be inferred from clothing and the tasks they are performing. Transactive memory theory is, thus, applicable to analyzing trauma resuscitation. Xiao et al. [25] used this concept to explain behaviors of trauma teams, while Faraj and Xiao [6] observed that trauma teams rely on collective memory. Although informative, their observations are qualitative only and not detailed. In addition, these studies did not consider opportunities for technological improvements, which is a key goal of our current work.

Hutchins' work on distributed cognition [13] suggests one mechanism of how group members maintain a meta-model of "who does what, when." Hutchins and colleagues studied sociotechnical work settings, such as the navigation bridge of ships and airplane cockpits, in which team cognition gets distributed across individuals, artifacts, and the setting. By externalizing individual memories and making them public using various artifacts, the team can reduce cognitive effort needed for maintaining working memory. Trauma resuscitation differs from other domains because few artifacts (e.g., trauma flow sheet and physicians' progress notes) help teams externalize their cognitive processes. Additionally, instruments and technologies in the trauma bay are rarely networked. While each helps to monitor a single parameter of patient state, they do not integrate into a single system that could be used to support workflow and communication or enable tracking changes in patient status.

METHOD

Research Setting

We conducted our study in a US Level-1 (the highest) regional trauma center over a 2-year period. This center admits >1200 trauma patients per year, among which about 600 need full trauma team mobilization. These patients have sustained major injuries from diverse causes, such as automobile accidents, falls, and gunshot and stab wounds.

To record videos of trauma resuscitations, we outfitted the trauma bay with two ceiling-mounted cameras and microphones. A wide-angle camera was mounted above the entrance to provide the view of the entire trauma bay. The second camera was mounted above the stretcher to capture the activities of workers gathered around the patient.

Participants

The fluid character of the trauma team makes it difficult to count the exact number of participants in our study. Based on the signed consent forms, we estimate that up to 225 healthcare providers were involved in our observations.

Line #	TIME (msec)	Medical Code	Intervention, Observation, and Memory-lookup Codes	Decision and Comm. Codes	ACTOR	ACTION	SUBJECT	COMMUNICATION
94	<225653>	C1	MM	RP	CCT	(finishes measuring BP)		130 over 66
95		S8	EXM		ORT	(examines PTN's legs)		
96			SEN	Q	REC	(talks to	TEAM)	Do you guys have anything other right now?
97			IR, SET		CCT	(approaches vital signs monitor, does something to it)		
98		C2		Q	TL	(talks to	CCT)	Do you have pulse on him?
99		B3, C2	IR	RS	CCT	(talks to	TL)	100%, heart rate 100
100				ACK	TL	(talks to	CCT)	Okay.
101		B1	EXM		PNR	(listens to breath sounds)		
102			SEN	Q	REC	(talks to	CCT)	(Name), do you have any vitals for me?
103	<286135>	B3, C2	IR	RS	CCT	(looks at the monitor, talks to	REC)	Yeah, 100% O2, HR 90

Table 1. Excerpt from a fully coded transcript. Role acronyms are shown in Figure 1.

Data Collection

We observed and videotaped 13 events, including 10 actual resuscitations and 3 on a patient simulator. Institutional review board (IRB) approval was secured before the study. To circumvent potential medicolegal risks associated with videotaping actual resuscitations, we erased videotapes of actual resuscitations (but not simulations) within 96 hours. When possible, we used idle moments to ask trauma team members for clarifications of our observations. Notes taken during the events were later augmented with details and summaries of our impressions. Copies of trauma flow sheets that represented patient status during the event were collected only for simulations.

Data Analysis

To analyze video recordings, we developed a transcription scheme based on the parallel columnar transcription scheme, which is commonly used in interaction analysis [14]. The extent and detail of our transcription scheme were determined by our analytic goals, as well as by the desire to capture the maximum amount of information given the limited time for video review. To gain insights into information flow and use of transactive memory in trauma teamwork, we focused on analyzing team activities, such as who talks to whom (actors vs. subjects), who does what (actors vs. tasks), types of information exchanged, and the use of artifacts. Although we transcribed nonverbal procedures, we could not perform detailed analysis, as in e.g., [22], due to the 96-hour limit for video viewing.

Resuscitations lasted between 20–30 minutes. Over 20 hours were needed to transcribe a 20-minute video that typically includes >400 discrete tasks or communications, showing the complexity of this work. We used Transana (http://www.transana.org/) for transcribing the videos. The transcripts were then transferred to a spreadsheet and segmented so that individual speaker turns and actions could be coded separately. Resuscitations were transcribed by a researcher who was trained in the processes of trauma care to acquire the skills needed to recognize and critically analyze the conduct of trauma resuscitations. Complete transcripts were then verified for accuracy by a trauma surgeon or nurse on our team. Given the 96-hour limit, we coded the transcripts after the videos had been erased. Coding was done independently by two researchers. Disagreements on codes were resolved in a discussion until consensus was reached.

Upon completion of transcription, each row was assigned one or more semantic codes. The codes belong to two coding schemes: (1) *medical task codes*, which represent the medical goals of the actions and provide the semantic context (e.g., oxygen administration, blood transfusion); and, (2) *control task codes*, which represent the behavioral aspects of the actions. These include *observation tasks* (physical examination, manual measurement, instrument reading, or sensing), *memory-lookup tasks* (situation recall, knowledge recall, and use of artifacts), *verbal communication* (directives, reports, inquiries, responses, clarifications, acknowledgments, message relays, and summons), *nonverbal procedures* (instrument setup, information recording, and handing or receiving objects), *decision-making and monitoring tasks* (judgment, praise, strategic planning, group decision making, leadership handover, task coordination, and coaching), and *intervention tasks*. The main categories in the control-task coding scheme were based on cognitive work analysis [23], while subcategories emerged (through an open coding method) from the materials collected during our observations of simulated trauma resuscitations. An excerpt of a coded transcript is shown in Table 1. In this example, line 99 shows a technician (CCT) responding (RS) to a previous inquiry (Q) by the team leader (TL). As their topic is about pulse rate, we put its matching medical code, which is C2. The medical code for oxygen saturation (B3) was also added since the CCT included its value in his response.

RESULTS

Role-Task Relationship

We first studied the nature of tasks performed by team members. Understanding who in the team does what task provided insights into the division of cognitive labor

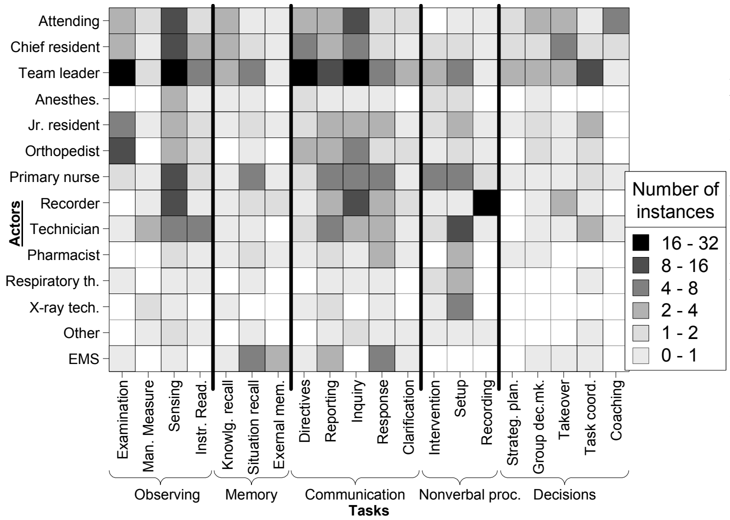

Figure 2. Frequency of task performance averaged over 10 resuscitation events.

because team members memorize information pertaining to their specialty.

Our results showed that individual control tasks were strongly associated with worker roles even with variations in teams and resuscitation scenarios. To depict their work graphically, we averaged the frequency of task performance over different trauma teams confronted with 10 different resuscitations (Figure 2). We observed that the averaged matrix did not become uniformly gray. It instead retained dark peaks and empty regions. This constancy of the role-to-task relationship suggests that variations in distribution of control tasks across teams and resuscitations are minor despite the need for adaptation to different scenarios.

Such constancy is also observed for medical tasks (not shown), which is not surprising because the caregivers carried out the tasks and responsibilities associated with their roles. For example, chest auscultation was mainly done by the team leader, attending physician or junior resident; intubation was always performed by an anesthesiologist with the assistance of a respiratory therapist; blood pressure and temperature were mostly measured by a technician, while primary nurses performed intravenous (IV) lines setup and draw of blood samples.

We were surprised to observe the constancy of role-to-task relationship for communicative and other generic tasks in our control-task coding scheme. To our knowledge, there is no specific training for communication- and memory-lookup related tasks in the trauma protocol (unlike for observing, deciding, and intervening procedures). Nevertheless, these tasks exhibit constancy across roles and events. For example, most inquiries originated from team leaders, attending physicians and recorders. This observation may be explained by the fact that the leaders (physicians) needed up-to-date information to make decisions. In contrast, the recorder needed information to document the event. While the recorder's table was positioned to be out of the way of team activities (Figure 1), this factor created difficulties in information gathering, which often resulted in repeated inquiries. In one event, we observed the recorder moving the table closer to the patient bed, which enabled the recorder to capture information more efficiently. Most reporting was done by technicians, primary nurses and team leaders. A possible explanation for this finding is that supporting staff play a crucial role in gathering patient information and communicating it to the rest of the team. The team leader coordinated the evaluation and treatment strategy based on received information, and reported assessments and decisions verbally to the team.

Collaboration vs. Command in Problem Solving

Our data showed relatively few *collaborative* problem-solving activities (Group decision-making column in Figure 2). This observation may be surprising because trauma teams face complex problems that, one would predict, require consultation of several team members and consensus building. Research has shown that critical decision-making in trauma teams is mostly concentrated in the current leader's role [15]. Our observations supported this previous finding as we observed that the physician in charge made all decisions and rarely consulted others.

The few cases of group decision-making that we observed showed that the supervisory team members did engage in collaborative problem solving during discussions of examinations, such as abdomen ultrasound exam for internal bleeding (FAST), administration of medications, and review of x-rays. Example below shows supervisory team members deciding on CT scan based on x-rays results:

JR (talks to TL) *We'll do abs CT, head, spine?*
TL, JR (approach x-ray workstation)
TL (talks to JR) *Don't know yet. We'll decide once we get the chest x-ray.*
TL (at the x-ray workstation, waits for x-ray images)
ATP (approaches x-ray workstation)
TL (examines x-rays, talks to ATP) *This actually looks okay. May be we could just CT the c-spine?*
ATP (points to the screen, talks to TL) *I would go for a full CT.*
JR (joins ATP and TL as they discuss x-rays)
TL (talks to JR) *We'll get the CT of head, spine, abdomen, pelvis, and c-spine.*

Use of External Memory Aids

Critical patient information is verbally conveyed to the recorder who maintains the trauma flow sheet, a form designed for documenting and archiving patient information and treatments. After the evaluation is completed, the flow sheet is transported with the patient and furnished to providers responsible for the patient's hospital care.

We uncovered two problems in keeping the trauma flow sheet current and complete. First, because of an outlying position (Figure 1), the recorder had trouble gathering information. Second, team members often failed to report their findings or current activities. Patient's medical history (existing allergies, medications, etc.) is an example of information that was often not reported to the team. We observed the team leader obtaining this information directly from the patient (if conscious) or EMS paramedics, early in the evaluation, but failing to report it to others. This failure to disseminate resulted in repeated inquiries by the recorder and other team members, prompting them to obtain this information again directly from the patient.

Although available during the resuscitation, artifacts such as the trauma flow sheet, the whiteboard outside the room, and the physicians' progress notes were only minimally used (Figure 3). The team members mostly relied on asking each other or the patient about important information throughout the event.

Our data showed only a few instances in which team members looked up the flow sheet (External memory column in Figure 2) during resuscitations.

> Instance 1: Chief resident (CHF in Figure 1) arrived late and inquired about the blood pressure. The team leader tried to recall the latest but failed. The recorder overheard them and read out the last reported blood pressure from the flow sheet:
> CHF (enters)
> CHF (talks to TEAM) *Do we have blood pressure yet?*
> TL (talks to CHF) *Yes we do, 190 something...*
> REC (looks at the flow sheet, talks to CHF) *191 over 78*

We also observed the use of trauma flow sheet towards the end of resuscitations when supervisory team members retrieved and examined images using the x-ray workstation (Figure 1):

> Instance 2: The leaders (ATP/CHF/TL) needed the patient's name to retrieve the x-rays. They approached and asked the recorder, who read it out from the flow sheet (patient name was initially obtained from the patient's driver license at the beginning of resuscitation):
> ATP (talks to TL) *Have we seen her x-rays or not?*
> TL (talks to ATP) *No, I didn't get a chance to look them up.*
> TL (approaches REC's table, talks to REC) *What's this patient name?*
> REC (looks at the flow sheet, talks to TL) *Jane Doe.*
> TL (talks to REC) *Jane Doe... thank you.*

The trauma flow sheet also served as an information source to some extent at the end of trauma resuscitations when physicians on the team generated their progress notes. Progress notes typically contain information about patient medical history, and both critical patient parameters and treatments received en route and during the resuscitation. However, rather than looking at the trauma flow sheet, physicians would often ask the recorder to read aloud information needed for their progress notes.

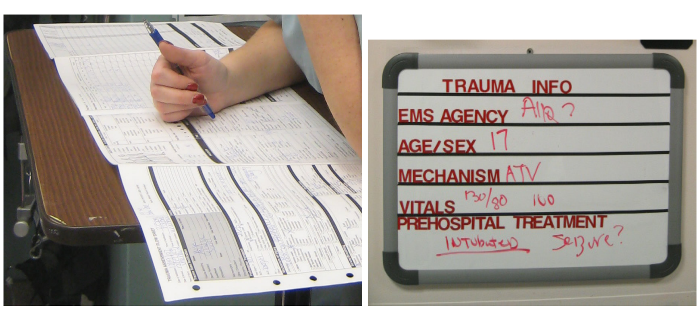

Figure 3. Information artifacts in trauma resuscitation: trauma flow sheet (left); whiteboard with pre-arrival information (right).

In contrast to trauma flow sheet that helps teams externalize their cognitive processes to some extent, the whiteboard at the entrance to the trauma bay is rarely used. We observed pre-arrival information written on this board only in two out of ten events. Even when completed, the whiteboard provided limited information (Figure 3) and did not obviate the need for gathering additional information from team members who were present at the time of paramedic's briefing.

Situation Recall

Our quantitative data supported our argument that team members memorize and recall situational information. Most of the situation recall (column in Figure 2) occurred while workers were responding to inquires. Supervisory team members mostly inquired about: what had been done (because they do not keep track of details such as the dosage or amount of medications and fluids given); how much time has passed since the last event (e.g., last blood-pressure measurement); and, for multi-step procedures, if steps have been completed or, if not, what was the current stage. Some examples of information types and actors involved in situation recall include:

- Team leader, answering the attending's inquiries about the mechanism of injury or treatments en route
- Anesthesiologist, specifying the tube size after intubation
- Primary nurse, answering physicians'/recorder's inquiries about intravenous (IV) access or mechanism of injury
- Pharmacist, reporting on administered medications
- Various team members answering inquiries about the designated CAT scan room. Although announced earlier in the process, some workers still ask for this information
- EMS, reporting on the accident details, e.g., whether or not the patient was restrained by a seat belt.

Information Sharing and Transactive Memory

The second aspect of trauma teamwork that we studied was the extent that the observed trauma teams used transactive memory. We investigated this issue by analyzing information flow and identifying the most common providers and seekers of information. An information provider is a member of the team who acquires information directly from the environment via observation tasks (physical examination, instrument reading, manual measurement, or sensing columns in Figure 2). An information seeker is a member of the team who inquires about patient information and team activities (inquiry or clarification columns in Figure 2).

Information category	Major providers	Major seekers
Mechanism of injury & pre-hospital information	EMS, Recorder	Team leader, Attending, Chief resident, Recorder
Patient demographic information	EMS, Patient, Recorder	Recorder
Patient medical history	Patient, Recorder	All leadership roles (ATP, CHF, TL), Recorder
Airway	Anesthesiologist, Respiratory therapist, Team leader	All leadership roles (ATP, CHF, TL), Recorder
Breathing	Team leader, Jr. resident	All leadership roles (ATP, CHF, TL), Recorder
Circulation/transfusion-fluids	Primary nurse, Team leader, Technician	All leadership roles (ATP, CHF, TL), Recorder
Disability	Team leader, Orthopedic, Jr. resident	All leadership roles (ATP, CHF, TL), Recorder
Physical examination findings	Team leader, Chief resident	All leadership roles (ATP, CHF, TL), Recorder
Vital signs	Technician, Recorder	All leadership roles (ATP, CHF, TL), Recorder
IV access	Primary nurse	All leadership roles (ATP, CHF, TL), Recorder
Treatments provided	Team leader	All leadership roles (ATP, CHF, TL), Recorder
Medications administered	Primary nurse, Pharmacist, Recorder	ATP, CHF, TL, Primary nurse, Recorder
Changes in patient status	Team leader	All leadership roles (ATP, CHF, TL)
Equipment	Technician	Primary nurse, Recorder
Team monitoring & teaching	Team leader, Jr. resident	Attending, Chief resident
Administrative issues	Recorder	Team leader, Primary nurse, Recorder

Table 2. Main information categories, who memorized this information (providers), and who inquired about it (seekers).

We observed that trauma team members rely heavily on specialization and delegation. Leadership roles (ATP, CHF, and TL), mostly relied on other roles (e.g., PNR, CCT, REC), to acquire, validate, memorize, and recall relevant information. Leaders delegated the task of memorizing instantaneous values of variables, such as vital signs, their past values (history) and possible trends. In addition, those in leadership roles delegated the tasks of remembering the timing to read-out new values, checking the validity of the recorded values, e.g., to detect values recorded by a loose sensor or a faulty instrument, and instrument troubleshooting. Because these same services were available to all other team members, rather than only in a dyadic relationship "leader-subordinate," this assignment of tasks helped avoid repetition. Xiao et al. [25] call this *transactive responsibility system* (TRS).

Inquiries (Q) and responses (RS) appeared to be the primary means of using transactive memory in trauma teams. Our analysis of the inquiries revealed 16 major categories with over 80 types of information needed in a typical event (Table 2). Some of the top information seekers (like team leaders and primary nurses) were also among the top information providers, Figure 4(a). This finding implies that these seekers acted as secondary providers, i.e., they responded to inquiries based on the information they acquired earlier from primary observers. For example, the superiors (attending or chief resident) often asked the team leader about the accident details. This type of query occurred because EMS paramedics, primary providers of this information type, left the ED once they debriefed the team and delivered the patient. Thus, the team leader needed pre-hospital information not only to be able to conduct evaluation of the patient, but also to be able to inform other team members who were either late or were busy with other tasks during patient handover.

We also observed low awareness of mutual information needs that resulted in inefficient use of transactive memory. This factor can be measured by using the concept of "anticipation ratio" [5]—the ratio of the number of communications providing information (RP) to the number of communications requesting information (Q). An anticipation ratio >1.0 suggests that team members are anticipating information needs of others and are "pushing" information towards them, while an anticipation ratio <1.0 suggests that little anticipation is occurring requiring team members to request ("pull") information from others [5]. In the 10 actual resuscitations that we transcribed, we observed an average anticipation ratio of 0.73±0.12 (range 0.63–0.94), suggesting that team members were poorly anticipating each other's information needs. We speculate that the resulting inquiries contributed to noise in the trauma bay and impaired communication because many questions were repeated. Our data showed on average 8.7 clarifications, 11.9 acknowledgements, and 2.6 message relays per resuscitation. About 12% of inquiries went unanswered, Figure 4(a). All these communication categories added to the general noise in the trauma bay and affected communication efficiency.

It is surprising that the team leader asked the attending very few questions, Figure 4(b), given that the team leader's role is subordinate to the attending's role. In contrast, the attending asked the team leader many monitoring and coaching questions. The team leader never asked the supervisor what to do. Due to the urgency of the situation, collaborative problem solving happened rarely—the team leaders were working under the ATLS protocol [1] and their activities were not free form.

Although communication between team members is essential for transactive memory, our findings suggested two problems: 1) due to the collaborative nature of assessment, it is critical that information is transferred to all team members; the absence of an effective alternate method mandated that most information exchange was verbal requiring team members to speak frequently and in short intervals; 2) because of overlapping voices and ambient noise, some speech was poorly audible which required team

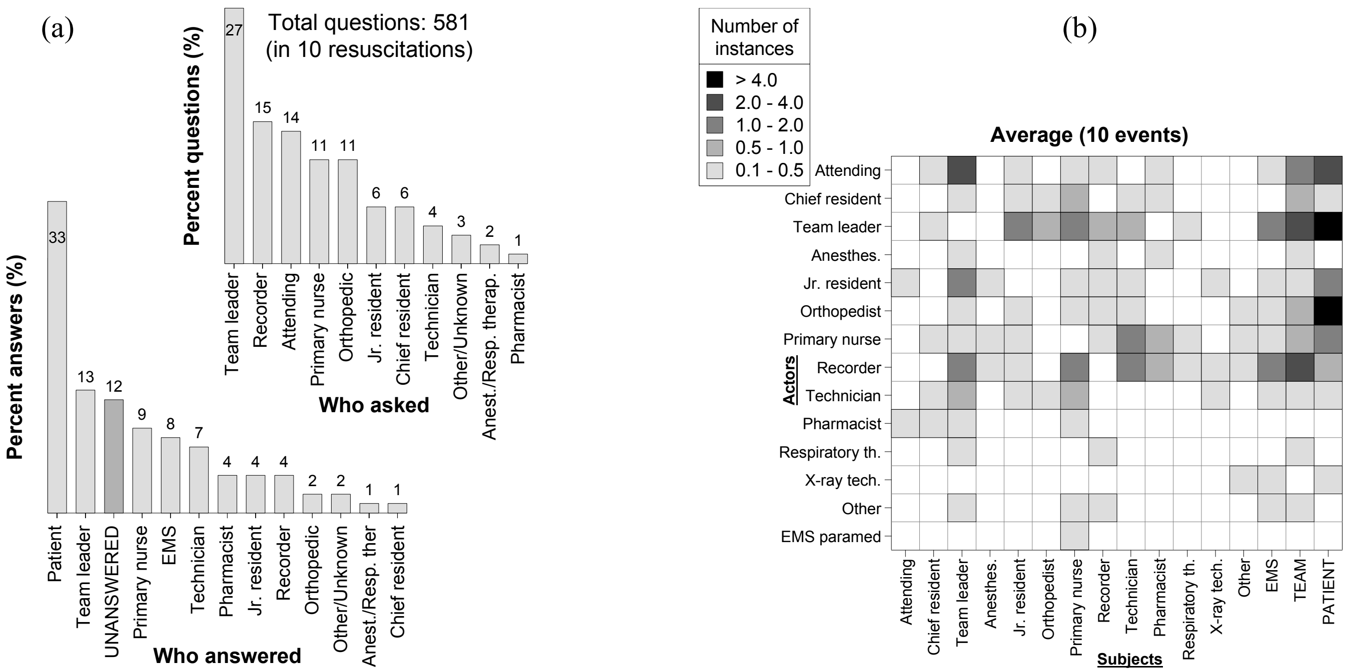

Figure 4. (a) Frequency of inquiries and responses, by role, in 10 resuscitation events. (b) Frequency of inquiries by who asked (actor) and whom the inquiry was directed to (subject), averaged over 10 resuscitation events.

members either to speak out loud or repeat their inquires, responses, and reports several times.

DISCUSSION AND TECHNOLOGY OPPORTUNITIES

Based on our initial observations, we have identified several opportunities for technology to address the information needs of trauma teams. As described above, trauma teams minimally rely on collaborative decision-making, with most decision-making concentrated in the command physician role. A group-decision support system (GDSS) does not, therefore, appear to be a high priority. We believe that a key role of technology will be to optimally display information for the team and facilitate information flow from providers to seekers, thus obviating the need for verbal communication in certain instances. It is known from other domains that information externalization to cognitive artifacts helps reduce the cognitive effort required of the team [13]. However, unlike in other domains, we found a surprisingly low amount of externalization of information. We speculate that the reason for this finding is that externalization requires time and effort, which are two very limited resources during trauma resuscitation. As a compromise, trauma teams appear to rely on verbal implementation of transactive memory. The current practice of relying heavily on other members to gather, store, and recall information may imply that the trauma teams may be disinclined to use new technological aids that require their direct interaction.

Information Displays for Distributed Cognition

Despite its limitations, speech is a critical component of communication in resuscitation and is the basis for transactive memory functioning. Our findings suggested that verbal communication strains team's cognitive capabilities, but is accepted as a solution because of the lack of an effective alternative.

Using verbal communication solely, allows only for *sequential* acquisition of the required facts. Since decision makers in trauma teams rely primarily on verbal communication, they collect pieces of information one-by-one until having enough to make a diagnosis and decide on treatment. This paradigm imposes a high load on their working memory. If different pieces of information were simultaneously visualized, there is a possibility of converting effortful computational tasks into relatively effortless perceptual recognition tasks. Selected information could be continuously displayed on a wall display. Other information could be displayed only when requested. For example, supporting team members could interactively retrieve and display needed information. Given the simultaneous visibility of all required pieces of information shown on a kind of "information dashboard," a decision maker could arrive at diagnoses and treatments more rapidly and accurately.

Interaction Design for Trauma Teams

Trauma teams already use technological aids in measurement and observation tasks. Unfortunately, these are not networked and their data are not digitally recorded and transferred to an electronic flow sheet. New information technologies could help in data recording and integration.

It is unlikely that all team members will equally interact with any new information system. Some members may be able to enter data and navigate computer screens and menus

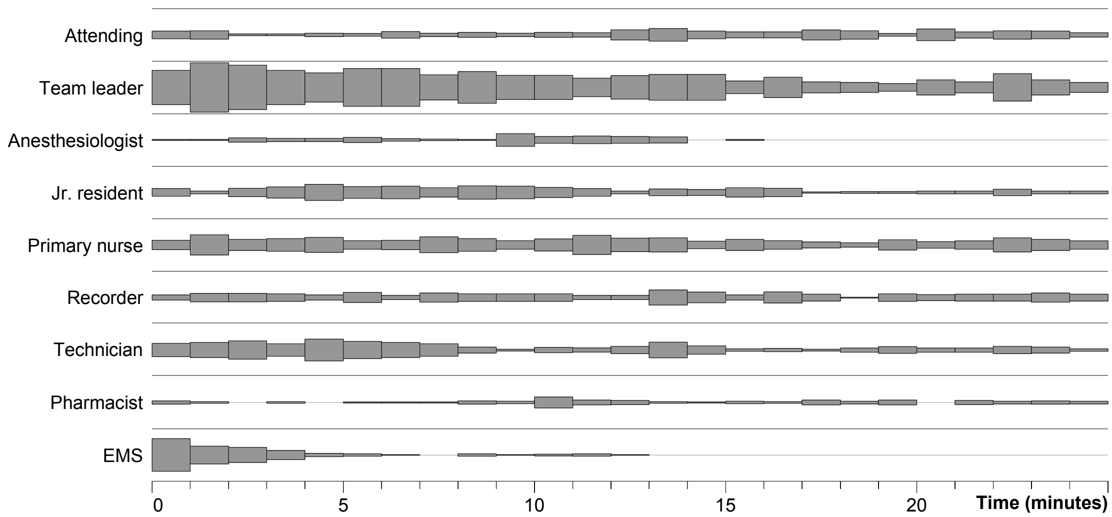

Figure 5. The evolution of worker's engagements over time averaged over 10 resuscitation events. The bar thickness symbolizes the average count of lines an actor appears in the transcript, per minute (values range: 0 – 8).

to retrieve information. Other team members will be too busy for this interaction and will most likely continue relying on others for information, i.e., they will continue relying on verbal access to team's collective memory. Although the simple metric in Figure 5 only partly captures the true workload of team members, it shows the team leader as the busiest busiest team member throughout the resuscitation. Thus, we can expect that the leader will at most look at information on wall displays, but not actively interact with the computer system. On the other hand, the recorder and attending physician are more able to look away from the patient and might be more receptive to interactive technology.

Of all team members, the team leader needs the greatest amount of information, to decide on appropriate actions and direct the team's activities. The challenge is to design an effective mechanism that allows the leader to retrieve and manipulate information efficiently while minimizing the amount of attention and cognitive effort needed for performing these tasks. One option is to have a team leader issue requests for information to other, less busy, team members who would interact with the system. It is unknown, however, how efficient and effective this type of *indirect* computer interaction will be. Another option is to equip the team leader (and other team members) with an earpiece and a close-talking microphone, allowing them to command the computer via voice. The challenge of this potential solution will be designing a speech recognition module to function in this noisy environment. At times, the use of a stethoscope may conflict with wearing a headset, requiring design of additional new technologies.

Automating Information Externalization in Trauma Bay

Regardless of how effective the user interface, requiring team members to interact directly with computers may not be the best option. Fortunately, direct interaction is not the only means for externalizing work information. Instead, automatic capture of teamwork information has become feasible using wireless sensor networks and "smart spaces," which have experienced great progress in recent years.

Physiological data from the patient could be automatically captured, and medications and other artifacts could be tracked using localization sensors, to avoid errors inherent in manual clerical data entry. Once externalized in electronic form, this information could be processed (data validated and trends detected), and stored. The externalized information could be visualized in graphical form on an "information dashboard." We envision that these technologies will offer a viable option for implementing distributed cognition and reducing the need for verbal communication in trauma bays.

CONCLUSION

In this paper, we presented qualitative and quantitative observations of transactive memory in trauma teams. Our study showed what kinds of information were needed by whom, and where the typical failures of communication appeared. We focused on analyzing verbal communication, which is the dominant form of interaction in the trauma bay because trauma teams have their eyes and hands busy with the patient and with instruments. Nonverbal communication, although rarely used for information exchange in trauma resuscitation, is important for physical and mediated coordination of activities and will be studied in future work.

We identified several opportunities for technology design, such as automating information gathering and clerical data entry using wireless sensor networks and "smart spaces," offering direct system interaction to the least-busy team members, and providing continuous display of critical information. Our continuing efforts include deriving system requirements for these technologies.

The CSCW contributions of this paper include: (1) advancement of knowledge about the use of transactive memory in small, collocated groups; (2) understanding of work practices of trauma teams for better technology design; (3) a method (transcription and coding schemes) to adapt to the medicolegal limitations of research in this domain; and, (4) an approach for quantifying team interactions that provides insight into work practices using a detailed representation of trauma teamwork.

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