Teamwork Errors in Trauma Resuscitation

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Human errors in trauma resuscitation can have cascading effects leading to poor patient outcomes. To determine the nature of teamwork errors, we conducted an observational study in a trauma center over a two-year period. While eventually successful in treating the patients, trauma teams had problems tracking and integrating information in a longitudinal trajectory, which resulted in inefficiencies and near-miss errors. As an initial step in system design to support trauma teams, we proposed a model of teamwork and a novel classification of team errors. Four types of team errors emerged from our analysis: communication errors, vigilance errors, interpretation errors, and management errors. Based on these findings, we identified key information structures to support team cognition and decision making. We believe that displaying these information structures will support distributed cognition of trauma teams. Our findings have broader applicability to other collaborative and dynamic work settings that are prone to human error.

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General Terms: Human Factors, Design

Additional Key Words and Phrases: Team errors, medical error, collocated teams, distributed cognition, system requirements, trauma resuscitation, healthcare

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1. INTRODUCTION

Analysis of human errors in complex work settings can lead to important insights into workspace design. This type of analysis is particularly relevant to safety-critical, socio-technical systems that are highly dynamic, stressful and time-constrained, and where failures can result in catastrophic societal, economic or environmental consequences (e.g., nuclear power plants or airplane cockpits). Researchers have studied a variety of factors that affect task performance and lead to errors in these environments. The main motivation has been to understand the nature of these application domains and

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provide design recommendations for supporting technologies [Johnson 1999]. Previous work has yielded progress in some domains where computer systems can now perform internal rule checks directly on user input to recognize and prevent errors. For example, a command to the system in an airplane cockpit to fly to a dangerously low altitude prompts a warning or blocks its execution [Hourizi and Johnson 2001]. This type of computer support requires sensors or other instrumentation that accrue situational information needed for detecting problems and issuing relevant warnings.

Trauma resuscitation is a high-risk medical environment that has received little study from the perspective of human work. The purpose of trauma resuscitation is to rapidly identify and manage potentially life-threatening injuries. It is a highly dynamic process prone to human errors even among experienced trauma teams [Clarke et al. 2000; Gruen et al. 2006]. Although considered a complex safety-critical, sociotechnical system, it lacks effective information technologies for supporting teamwork. Unlike a plant control room or an airplane cockpit, there is no computer to capture worker activities and monitor for errors. Errors are now prevented mainly through provider experience, training, and redundancies in the evaluation process. Trauma bay instruments, such as vital signs monitors and other sensors, only provide data about patient status. There is no computerized support in decision making, which currently relies on knowledge and judgment. Team members must remember to monitor screens and observe trends in the data, with audible alerts only for extreme values. Monitoring of instruments is visual or aural (listening to the relative tone of continuous alert sounds). Patient findings, test results, and observations are called out and exchanged verbally between pairs, small groups, or the entire team. Critical patient data are usually recorded manually even when digital devices are used in data acquisition.

In this study, we seek to understand the causes of human errors unique to teamwork in this domain. We examine the characteristics of teamwork to understand why and when team errors occur in trauma resuscitation. In doing so, we focus on work organization and information flow among team members. We use distributed cognition theory [Flor and Hutchins 1992; Hutchins 1995; Rogers and Ellis 1994] to guide our reasoning about the ways in which trauma teams' performance can be improved. Studies of cognitive systems, such as ship navigation and air traffic control have shown the importance of external representations of task information and shared knowledge about team activities for efficient teamwork. Our results show that trauma teams currently experience challenges because of a low degree of task information externalization. This observation highlights the need for improving trauma teamwork by developing technological solutions that help externalize critical information at the system's (or trauma team's) level.

To aid our analysis of teamwork errors, we propose a model of trauma teamwork and derive a novel error-classification scheme. By identifying errors and their causes in a highly team-dependent work such as trauma resuscitation, we hope to gain a better understanding of the requirements and challenges that computerized support must meet to facilitate cooperative work in high-risk environments. As the outcomes of this research, we propose two key information structures that need digital representation and display to better support team cognition and diagnostic reasoning of trauma teams.

We distinguish individual and team errors as follows. *Individual errors* happen when a person either works alone or in a team but isolated from others. Unlike individual errors, *team errors* happen when there is a minimum of two people collaborating and interacting, such as exchanging information or working together on the same task.

As a research setting for studying human work, trauma resuscitation has several important features. First, it is a stressful and dynamic environment that shares a number of attributes with other safety-critical, socio-technical systems including (a) an unpredictable set of problems, (b) the occurrence of incomplete or conflicting information, (c) multiple and sometimes conflicting goals, (d) intense time pressure, (e) a low margin for error, and (f) variable knowledge and expertise among team members. Second, trauma resuscitation is highly dependent on teamwork and is error-prone, making it ideal for studying team errors. Finally, the trauma bay provides a valuable site for the study of cooperative work because the task-demands change rapidly and vary in nature, predictability, and difficulty. These features contrast with those in other clinical settings in which patient management relies on existing rather than emerging information.

The article is organized as follows. We first review other studies on collaboration and human errors in safety-critical domains, followed by an overview of trauma resuscitation. We then describe the methodology and research setting for our study. Following this description, we present a model of trauma teamwork that served as an analytical framework for identifying team errors. Next, we discuss our results and describe how we applied our team-error taxonomy to the observed errors. Subsequently, we discuss the implications of our findings for quality and efficiency of teamwork in trauma resuscitation. We conclude by discussing requirements and challenges in technology design to support collaborative work in this and other safety- and time-critical settings.

2. RELATED WORK

Prior relevant work spans three research areas: (i) study and modeling of time-critical teamwork; (ii) analysis of human error and errors in trauma resuscitation; and, (iii) development of computerized support in medical settings.

2.1 Study and Modeling of Time-Critical Teamwork

Several studies of collaborative work in human computer interaction (HCI) and computer-supported cooperative work (CSCW) have addressed time criticality outside of the medical domain. Studies of traffic control rooms [Berndtsson and Normark 1999; Heath and Luff 1992], trading room floors [Heath et al. 1993], emergency response dispatch centers [Bowers and Martin 1999; Pettersson et al. 2004], and firefighters [Landgren 2006] identified essential features of collaborative work, such as continuous flow of information among workers, simultaneous monitoring of co-workers' activities, and reliance on technologies that facilitate collaboration. Similarly, in his study of collaboration on a ship navigation bridge, Hutchins [1995] found that navigation teams maintain system robustness by redundant distribution of knowledge among team members, members' access to one another's activities, and mutual monitoring and assistance. While this line of research has deepened our understanding of collaborative work in time-critical work settings, it focused on the work processes and strategies that help teams maintain failure-resistant performance. In contrast, we analyze the situations in which failures occurred and seek to understand the causes of those failures.

Studies of collaborative work in medical settings have examined both distributed and collocated teams, but over longer periods and long-term activities, including work coordination in surgical suites and hospital wards [Bardram 2000; Bardram and Hansen 2010; Bossen 2002; Tang and Carpendale 2007], and intensive care units (ICU) and emergency departments (ED) [Paul and Reddy 2010; Reddy et al. 2001]. Although these studies do not explicitly focus on human errors, they provide an in-depth understanding of routine medical work. Because this routine work occurs over extended periods and involves distributed access to information, medical personnel are more likely to obtain high-quality information and make well-informed decisions. In contrast, our work examines errors in the context of collocated teamwork in a time-critical situation of trauma resuscitation, where time pressure plays a crucial role in shaping information sharing, work coordination, and decision making. In addition, rather than focusing on macrocoordination issues like scheduling, we focus on short-term tasks requiring microcoordination, such as intubation, fluid administration, and establishment of intravenous (IV) access. Our contribution here is in identifying team errors in time-critical work of collocated teams in a setting characterized by a low level of distributed cognition. This setting contrasts with other kinds of time-critical work, both medical and nonmedical, where workers rely on physical representations of situational information to conduct their work.

2.2 Analysis of Human Error and Errors in Trauma Resuscitation

Efforts to study human error were motivated by incidents in nuclear power plants and airplane crashes in the 1970s and 1980s [Sheridan 2003]. Rasmussen [1983] developed a model of human cognitive information processing, termed the "skills-rules-knowledge" (SRK) framework. Skills and rules operate quickly and effortlessly, while knowledge-based processing is slow and requires significant cognitive effort. Klein et al. [1993] developed a model of human decision making in natural settings, known as "recognition-primed decision" (RPD) model. They found that experienced performers make 80 to 90 percent of their decisions in a rapid, intuitive process of recognition and application of expert rules, and rarely deliberate or compare options. Similar modes of decision making have been found in a variety of dynamic contexts and have been described using psychological constructs such as, "pattern matching" [Rouse 1983], "rule-based behavior" [Rasmussen 1983], and "perceptual heuristics" [Kirlik et al. 1993, 1996].

Most theoretical studies of human errors that followed were based on Rasmussen's SRK framework. Reason [1990] attributed individual errors to cognitive underspecification, such as incomplete or ambiguous input information, fragmentary cues for memory retrieval, and incomplete or inaccurate knowledge. In contrast to individual worker's errors, little is known about errors that are unique to teamwork. Previous work offers a preliminary theoretical framework for understanding team errors [Sasoua and Reason 1999; Trepess and Stockman 1999], but does not explain how or why team errors happen. Additionally, these studies do not investigate technology requirements needed to achieve practical system designs [Johnson 1999].

The existing classifications of errors in trauma resuscitation [Clarke et al. 2000; Gruen et al. 2006] are "problem-centric" and focus on errors in medical tasks and their effect on the patient. While these taxonomies are useful for tracking the impact of errors, neither provides a view of why errors occur and how information technology might prevent or correct them. To guide the development of solutions for reducing errors, a model is needed that explains and categorizes errors in collaborative work. This study is focused on errors that are unique to teams rather than individual workers.

2.3 Development of Computerized Support in Medical Settings

The report by the Institute of Medicine (IOM) estimated that up to 98,000 people die in the US hospitals each year as a result of medical errors [Kohn et al. 2000]. Most of these errors have been contributed to the fragmented nature of health care delivery, faulty systems, and poor communication. Hence, technological solutions proposed or developed over the past decade mainly focused on improving information access, communication, awareness, and coordination of medical work [Bardram 2009; Bardram and Norskov 2008; Bardram et al. 2006; Bates and Gawande 2003; Leape et al. 1995;

Moss and Xiao 2004; Wears et al. 2007; Wilson et al. 2006; Xiao et al. 2001]. An early work by Leape et al. [1995] examined the underlying causes of errors during drug administration and found that many errors were prevented by staff who were alert during information handover in the process of drug ordering, distributing, and administering. Leape and colleagues recommended augmenting this aspect of team performance by computerized support, where all activities and information exchanges are recorded and checked. Bates and Gawande [2003] discussed human errors in the context of drug administration safety as well. To improve the process, they proposed better access to reference information. Although feasible in many medical settings, this solution is not applicable to trauma resuscitation because time pressure often prevents using reference information.

Previous studies of medical work in CSCW and HCI have recognized the need for better representation of task information, and have focused on digitizing paper artifacts to allow for an easy access to this critical information. Bossen [2002] and Bardram et al. [2006] examined the use of care-journal and patient record as the two central artifacts for task coordination and information transmission in hospitals. They found that important task information also includes general awareness of "who is around" or "what is going on." Bardram et al. [2006] developed a system called AwareMedia to support this general awareness in an operating ward by informing the medical staff about surgeries in progress, their status or the activity level, other scheduled events that may be relevant, and the whereabouts of their colleagues. Furthermore, Bardram [2009] considered activity-aware applications for improving medical work, but focused on tasks and activities over long time periods and with no time pressure. The advantages of digitizing process information are also seen in other domains, such as nuclear power plants or airplane cockpits, where information systems can check for constraints and enforce procedures, legibility, and timeliness. We believe that digital representations of proper information structures in trauma resuscitation will offer the same benefits already seen in some medical and other safety-critical domains. Because trauma teams mainly rely on collective memory and rarely on paper artifacts [Sarcevic et al. 2008], we first need to identify the types of information that need to be externalized and then digitized.

3. TRAUMA RESUSCITATION OVERVIEW

Trauma resuscitation takes place in a designated room in the emergency department, called the "trauma bay." The main goal of trauma resuscitation is to rapidly stabilize the patient, determine the extent of the injury, and develop a treatment plan to be carried out during hospitalization. While external injuries are relatively easy to diagnose, internal injuries are often difficult to detect and may lead to adverse outcomes if not identified and treated on time. A key challenge for trauma teams is diagnosing internal injuries quickly and accurately. To illustrate the potential urgency of diagnosing internal injuries, Clarke et al. [2002] found that each minute of delayed care could increase mortality by as much as 0.5 percent among patients with major chest injuries. Because of the need for rapid diagnosis, the trauma bay lacks more accurate but time-consuming imaging and testing methods for patient evaluation found in other hospital units. Even a patient's weight, a variable often needed for determining medication dosages, is inconvenient to measure and has to be guessed or inferred from the patient's height [Shah et al. 2003].

3.1 Patient Evaluation and Trauma Teams

The resuscitation process is guided by the Advanced Trauma Life Support (ATLS) protocol [American College of Surgeons 2008]. ATLS aims to achieve a rapid and

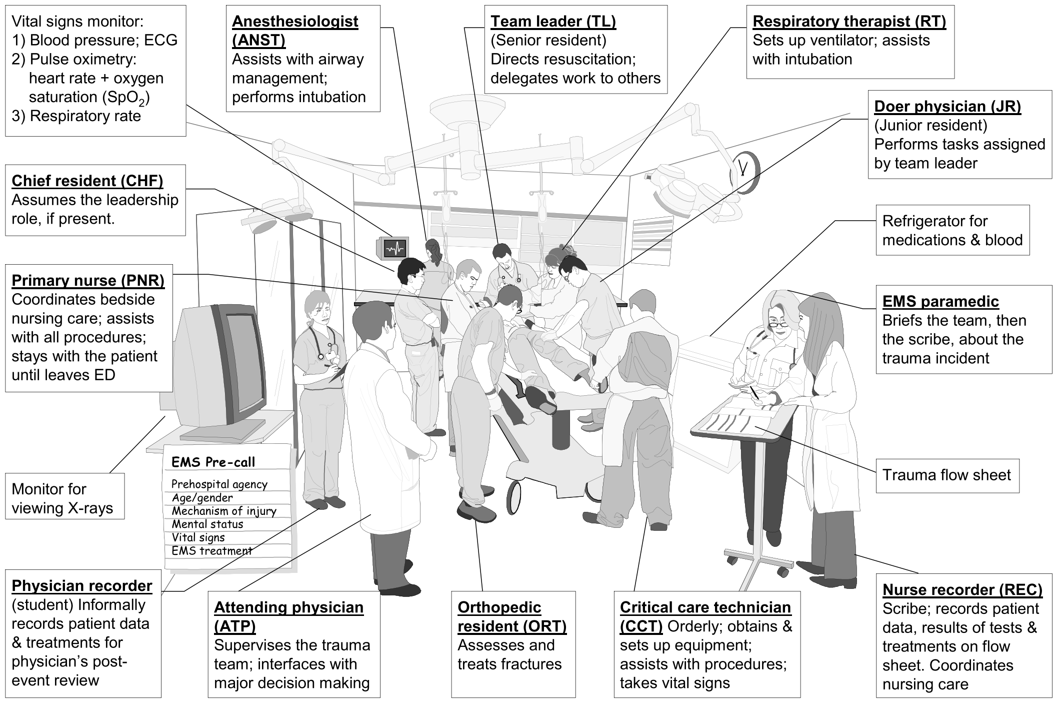

Fig. 1. Emergency department (ED) trauma bay: actors and artifacts in a resuscitation event.

reliable diagnosis by thoroughness and prioritization of resuscitation activities. It consists of two phases: the primary and secondary surveys. In the primary survey, the trauma team evaluates the patient for a patent airway (Airway), and assesses ventilation (Breathing), perfusion (Circulation), and neurological status (Disability). The patient is then completely disrobed (Exposure) for identifying injuries that may not be apparent initially. The ABCDE steps are followed by a detailed physical examination for other injuries (secondary survey). While ATLS is conceptually conceived and taught as a hierarchically-ordered process, each step may be repeated as patient status changes or more information becomes available. ATLS does not specify team members' responsibilities but instead imposes a framework that the team should follow. Because it deals with prioritization of evaluation tasks and description of treatment procedures, the ATLS protocol is patient- or problem-centric, rather than team-centric.

To avoid performance of redundant tasks, most trauma centers have specified the roles and responsibilities of team members, allowing only limited variation (Figure 1). Similar to teamwork in other high-risk work settings, trauma resuscitation involves a hierarchical team structure [Klein et al. 2006]. The team leader, usually a senior surgery resident, coordinates work and ensures that the correct priorities are addressed. The role of the team leader can change between residents and attending physicians based on the patient state, and the skills and availability of the individuals present in the room. The leader is assisted by a junior resident who performs hands-on evaluation and treatment tasks. An anesthesiologist manages the patient's airway, and an orthopedic surgeon is responsible for musculoskeletal injuries. The primary nurse is dedicated to patient care while the nurse recorder documents the event on a paper flowsheet. More details on roles and responsibilities of trauma team members are available in Sarcevic et al. [2008, 2011].

The patient evaluation usually lasts between 20 to 30 minutes. Upon completing the evaluation, the team prepares for the patient transfer to other hospital units as needed. Patients requiring immediate surgical care are taken directly to the operating room, while other patients are taken to CT scan to evaluate for internal injuries.

3.2 Distributed Cognition in Trauma Resuscitation

The work of trauma teams is now only partially supported by physical representations of task information. We divide this externalized information into two groups: *situational information* and *medical reference information*.

Situational information that is currently externalized or available by default includes the following.

— Patient vital signs displayed on a vital signs monitor in real time. The monitor also emits a periodic audio tone, with a tone pitch encoding blood oxygen saturation (SpO2) and a tone frequency encoding pulse (heart rate).
— Patient body, a key source of situational information. For example, changes on the patient (e.g., behavior, skin color) prompt actions; artifacts on the patient body imply team activities (e.g., one can see if the patient has a chest tube or IV access). This information, however, is only partial because details or historic information are not visible (e.g., tube size, time of chest tube insertion, and who performed it).
— Trauma flowsheet, used for archiving patient information and activities during resuscitations. This artifact is seldom used for real-time decision making.
— Timer and clocks on the wall help in monitoring the duration of treatments.
— Fluid bags are examined for the amount of administered fluid.
— Sign-in board provides information about the present team members. Prehospital information board shows data received during transport.
— Positioning of equipment indicates current or planned actions.

It may appear that trauma teams use many physical artifacts ("physicalities") where task information is externalized. Yet, we found that they mainly rely on collective memory and verbal communication for information sharing and decision making [Sarcevic et al. 2008]. Our analysis showed on average 55 inquiries per resuscitation over 18 events, most of which sought information about the patient status, vital signs, administered fluids and medications, and patient medical history. Some verbal communication may simply be a preference for asking over looking up information from various sources. We observed, however, that even team members who responded to inquiries were often ill equipped to provide correct and complete answers. Most of the past or planned activities cannot be inferred by looking at the patient-bed area; important details about procedures are usually not visible, including tube sizes, or the type and dosage of medication that is being administered. Although critical, temporal information about task trajectories is also not readily available. For instance, we observed a case in which a nurse was unsure if the information on the prearrival status board was for the current or a previous patient. Even if most of the critical task information were already externalized, none of it is currently in a computerized form that allows automatic integration and analysis.

Time pressure in a work domain affects the type and the extent to which task information is externalized. Unlike personnel in other hospital units, trauma teams minimally rely on paper-based information artifacts. The lack of such artifacts may explain why information technologies have not yet had success in the trauma bay: because there is no practice-based precedent for externalizing information from paper artifacts, there are no clear targets for digitization. A key contribution of our study

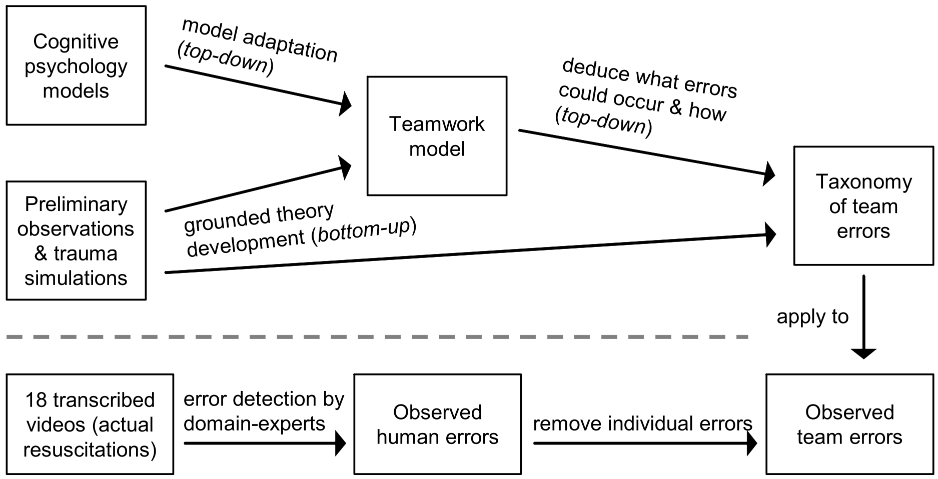

Fig. 2. A roadmap depicting how the research in this article was performed.

is in identifying critical information structures that require digitization for trauma teamwork support.

4. CURRENT STUDY

4.1 Research Site

Our research site was a top-level (Level 1) trauma center in the Northeast US region, located in a major hospital complex. Level 1 trauma centers are preferred sites for initial triage of injured patients and are major referral centers for injured patients initially treated at other hospitals. Our trauma center admits over 1200 trauma patients per year, among which about 600 involve full trauma team activation. It uses the same staffing and procedures as other high-level trauma centers in the US. Patients treated at this trauma center have sustained a wide range of injuries including those caused by car accidents, intentional violence (e.g., gunshot or stabbing wounds), or falls.

4.2 Methods

To gain the requisite knowledge of the nature of trauma teamwork, we used several techniques for studying the domain. We conducted a two-part observational study of trauma resuscitation over a two-year period (April 2006–May 2008) (Figure 2). Data collection included detailed observations of 3 simulations and 60 actual resuscitations across morning, evening and night shifts, clarifying information through informal conversations, and jotting down notes. Observed events involved a wide range of injuries and lasted on average 23 minutes. Informal interviews with trauma team members usually took place during down time. Interviewing immediately after the events was difficult because physicians and nurses followed the patient to the next hospital unit.

In addition to observations, we videotaped 21 events, including 18 actual resuscitations and 3 that used a patient simulator. To circumvent the risks involved in videotaping live resuscitations, such as patient privacy and medico-legal concerns, we ensured that written records produced during the study excluded resuscitation dates, times, and any personal or other information that could permit identification of a patient, specific resuscitation, or a team member. As a result, Institutional Review Board (IRB) approval was secured, but required that we erase video recordings within 96 hours. Because of this limitation, we were able to videotape and analyze in detail only one third of the observed events. Trauma events were recorded using two ceiling-mounted cameras with microphones, one positioned to record the view of the entire trauma bay and the other to record the view above the patient stretcher. Informed consent was obtained in advance from 243 healthcare providers who participated in trauma resuscitations.

In the first phase of our study (top row of Figure 2), we analyzed field notes from nonvideotaped resuscitations and three simulations to understand work processes during resuscitation. Following the strategies for grounded theory development [Glasser and Strauss 1967], we used an open coding technique to identify the substantive categories of teamwork activities. The initial categories described inefficiencies and errors in information acquisition, communication, decision making, and intervention. Examples included failures to report findings from patient examination, communication breakdowns, misdiagnoses, and prolonged procedures. We then used "theoretical axes" derived from cognitive psychology theories to relate the substantive categories and form a model of teamwork. The teamwork model, (described in Section 5) provided an analytical framework for identifying team errors and helped us explain why the observed errors occurred. We used theoretical axes instead of axial coding of Strauss and Corbin [1990], because we believed they were better suited for our problem domain [Kelle 2005].

After we derived the taxonomy of team errors, we conducted a systematic study to verify it on 18 actual resuscitations that were videotaped, transcribed, and analyzed in detail (bottom row of Figure 2). The first author, who was trained to recognize resuscitation workflow, produced detailed transcripts of recorded events. For each resuscitation, we transcribed several hundred steps, noting who said or did what. Transcription was based on the parallel columnar transcription scheme commonly used in interaction analysis [Jordan and Henderson 1995]. Each discernable action of each team member was transcribed in a separate row. Each line included the type of action or utterance (e.g., instrument reading, diagnosis, inquiry, treatment) and identified who performed a task or spoke based on their role. Video recordings were discussed and transcripts were verified with domain experts on our research team to assure data quality.

Upon completing transcriptions, three trauma surgeons on our research team identified medical errors committed by the trauma team without distinguishing individual- from team-based errors. Because our focus was on team errors, we filtered out individual errors identified in the transcripts. There were on average 19 errors per resuscitation [Tinti et al. 2008], of which about 50% were considered team errors. We then analyzed how well these team errors fit into our taxonomy. We next describe the development of our teamwork model and team errors taxonomy.

5. A MODEL OF TEAMWORK AND CLASSIFICATION OF TEAM ERRORS

We developed a descriptive model of trauma teamwork to simplify our observational data and highlight important relationships among actors and events. The purpose of this model was not to mimic trauma team activities. Rather, it served as an analytical tool that helped us systematize the problems and errors observed during trauma teamwork. The model represents a grounded theory derived from our observations, with cognitive psychology theories serving as the "theoretical axes" for model development [Kelle 2005].

5.1 Theoretical Background: Applying Cognitive Theories to Teamwork Modeling

The starting point for our trauma teamwork modeling was the dichotomy between cognitive processes as *intuitive* vs. *analytical*, known as System 1 and System 2,

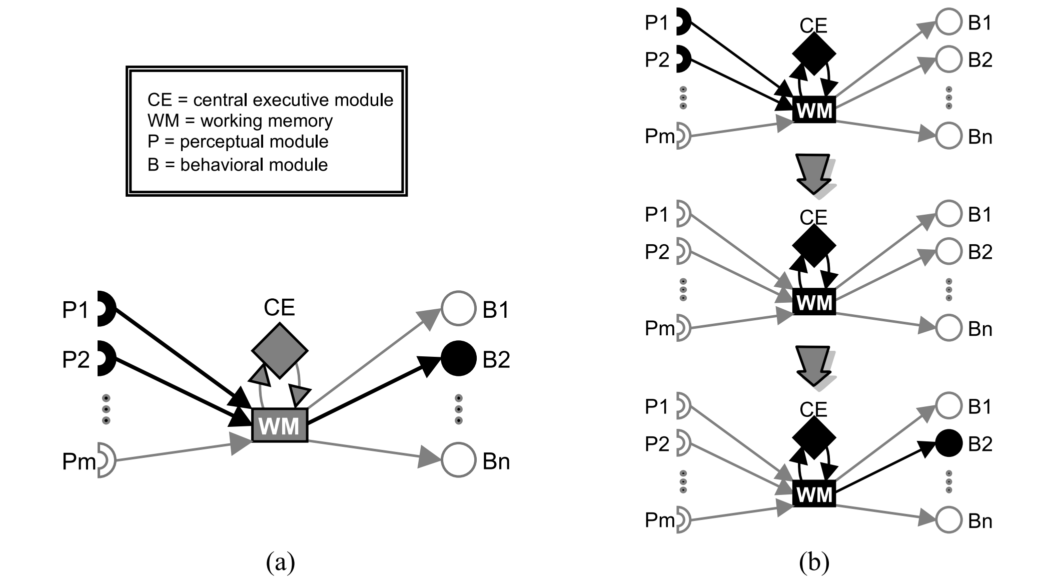

Fig. 3. Modular dual processes of cognition: (a) System 1 is works by automatic recognition. (b) System 2 works by multistep, rule-based deliberation. The modules highlighted in black are active in a given step. System 1 imposes relatively light load on working memory and central executive (shaded gray).

respectively [Evans 2008; Evans and Frankish 2009]. System 1 operates by associating sensory input and action, based on pattern recognition. System 2 operates by sequential application of rules, using working memory to store the intermediate results. (The distinction between associations and rules is not straightforward [Gigerenzer and Regier 1996].) To illustrate theses dual processes, suppose that we need to determine the product of 8 and 7. System 1 would simply apply the rule {IF 7×8 THEN 56} from a memorized multiplication table. Alternatively, based on the definition of multiplication as repeated addition, System 2 would apply these rules:

$$\{\text{IF } a \times b \text{ THEN} a \times b = \underbrace{b + b + \ldots + b}_{a}\} \text{ and } \{\text{IF } x + y + \ldots \text{ THEN (addition rules)}\},$$

where “addition rules” specify how to arrange numbers in rows aligned to the right, add the columns starting with the rightmost one, and how to deal with the carry. We also assume that the person knows the addition table for numbers 0 – 9. As seen, System 1 uses working memory lightly, only to gather the inputs and apply recognition on them. System 2 uses working memory extensively for storing the intermediate results while applying a series of rules. System 1 is believed to be “intuitive” because its association rules are difficult to articulate. Conversely, System 2 rules are consciously known.

Another idea we applied to our modeling concerns the division of cognitive labor, known as the *modularity of mind* [Fodor 1983]. Most cognitive psychologists believe that some cognitive mechanisms are modular, particularly perceptual and motor behavior systems. Fodor [1983] argued that higher level, or “central,” cognitive processes are not modular, and no further modularization is possible. Figure 3 depicts the functioning of dual cognitive processes in a modular fashion. Perceptual modules (P) encode the input information into working memory; central executive (CE) performs pattern matching of IF conditions and puts THEN actions into working memory; behavioral modules (B) convert actions from working memory into behaviors.

Because trauma resuscitation is team-based, we adopted the notion of *distributed cognition* and considered the trauma team as a distributed cognitive system, or a “team mind.” In so doing, we could view different team members as having the roles of different modules in Figure 3. The team leader corresponded to central executive, while other team members performed evidence gathering (perceptual modules) or treatments (behavioral modules). Although we could not directly observe whether an individual mind functioned as System 1 or System 2 at any time during resuscitation, we could do it for the team mind, based on communications and interactions among team members.

We knew from our previous observations that trauma team members’ activities were mostly based on automatic recognition and application of expert rules [Sarcevic et al. 2008]. Deliberative behaviors, where the team discussed alternative approaches, rarely occurred. Trauma teams have little time for free-form exploratory, deliberative behaviors, and instead follow the ATLS protocol. Others who studied decision-making in safety-critical environments [Klein 1998] have also found the dominance of recognition-based behaviors. Therefore, knowledge-based work is dominated by System 1 operation and there is little reliance on System 2 operation. Given the importance of System 1 thinking, we needed to determine how effective this mode of distributed cognition is in trauma teamwork and what can be done to improve it. Additionally, by separating recognition-based and deliberative behaviors from the team-mind perspective, we were able to examine teamwork errors associated with each type of the behavior.

Most cognitive psychologists agree that human reasoning can be represented with mental rules of the type IF *condition* THEN *action* [Harré 2002; Quinlan and Dyson 2008]. What is debated is whether human brain is rule-following (brain works by computing rules) or rule-governed (brain functioning can be described by rules, but it does not necessarily compute rules). This issue is out of the scope of our current article.

5.2 A Model of Trauma Teamwork

We derived our model of teamwork based on our data and on cognition theories presented above. We use the analogy in Figure 4 to help illustrate the functioning of our model of “trauma team mind.” In the model, trauma team members work towards satisfying resuscitation goals by applying rules of the type:

IF symptoms-observed **THEN** diagnosis **DO** apply-appropriate-treatment

For example, if the patient is diagnosed with a pelvic fracture that resulted in internal bleeding, a treatment may be to administer intravenous fluid or blood, or wrap the pelvis with a specially designed strap to stabilize the fracture and reduce bleeding.

There are two parts of rule application: (i) recognition of a diagnosis and (ii) execution of a treatment. Diagnosis recognition starts with observations, where different team members gather patient information from the environment. This activity can be visualized as a puzzle-solving analogy, in which team members collect and assemble the puzzle pieces, while the team leader works on solving the puzzle (Figure 4(a)). Initial observations of trauma resuscitations showed that acquired facts about the patient were communicated to the team leader or to the whole team, and presumably stored in team’s collective memory [Sarcevic et al. 2008]. The team leader (central executive) then used the gathered facts to perform pattern matching on the IF conditions and make a diagnosis.

Diagnostic process during resuscitations has two important characteristics. First, the goal is to reach a diagnosis quickly. In Figure 4(a), some pieces provide key information about the puzzle content (“strong cues”), while others provide little information (“weak cues”). The leader should actively steer the evidence-collection process by

(a)
Diagnosing

(b)
Treating

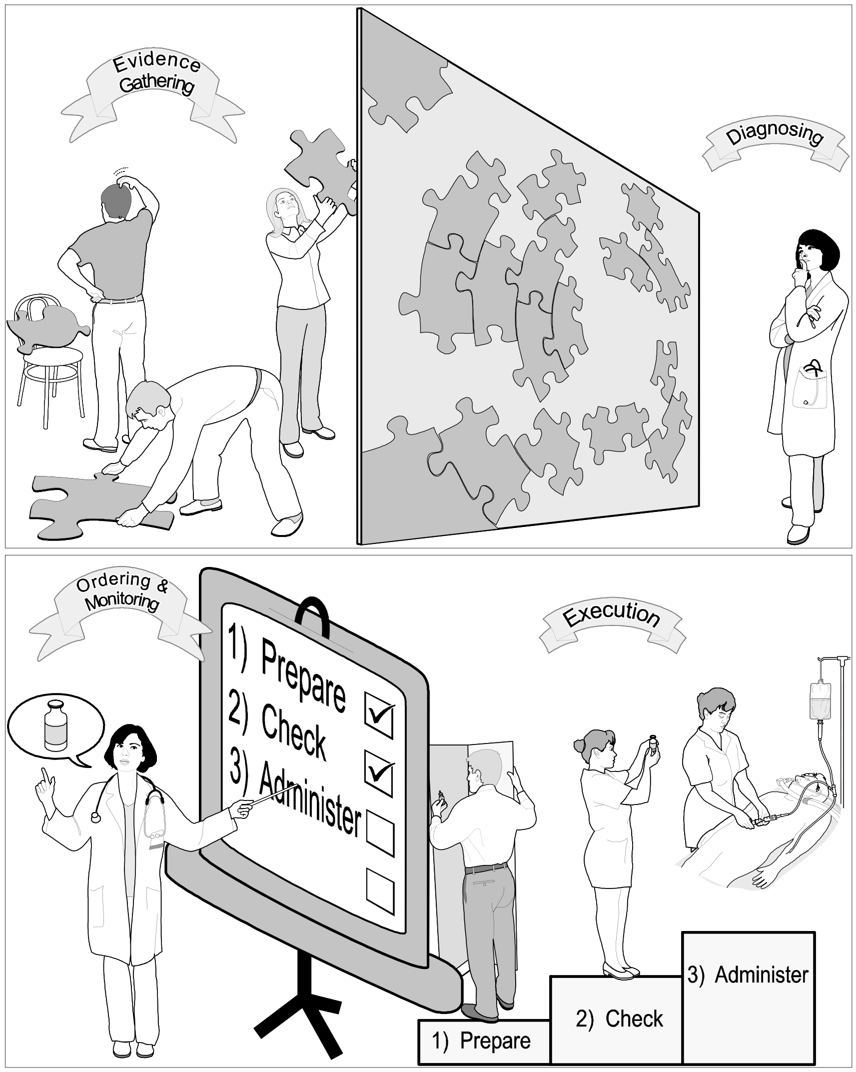

Fig. 4. A simple analogy for rule-based teamwork behaviors in trauma resuscitation. Team leader diagnoses the problem (a), then orders and monitors the treatment (b).

hypothesizing potential diagnoses, rather than passively wait for random pieces; the team then seeks new evidence to help support or refute the hypotheses. Our interviews with team leaders confirmed a known fact that generating diagnostic hypotheses is critical for successful diagnosis [Norman 2009]. To avoid treatment delays, the leader should attempt diagnosing based on partial or weak signs of injury, instead of waiting for strong cues that would make the diagnosing straightforward. Second, we observed that gathering evidence takes variable and relatively long time, sometime tens of minutes. As discussed later, this fact has important consequences for memorization of accrued information.

The second part of rule application involves applying a treatment to the diagnosed problem (Figure 4(b)). The leader assigns treatment tasks and monitors their execution. We observed that most treatments involve multiple steps performed by different team members. For example, there are several steps in medication administering: the dosage and route is ordered by a physician, it is prepared by a pharmacist and then given to a nurse who checks it for correctness, administers it, and reports that the medication has been administered. The team leader must ensure correct and timely completion of all steps because subsequent steps depend on successful completion of previous steps.

A central mechanism of cognition is working memory (Figure 3), which is known to be limited [Quinlan and Dyson 2008]. In distributed cognition, a team's working memory comprises working memories of individuals as well as externally available information (described in Section 3.2 for the trauma bay). The capacity of a team's working memory is somewhat larger than any individual one. Working memories of individuals do not combine additively because all members of the team are subject to the same or similar situational information, resulting in overlapping contents of their working memories. Similarly, a team's capacity for pattern matching of rule conditionals is greater than any individual one, but only moderately, because only a few team members possess expertise in emergency medicine. To successfully match the pattern of symptoms with a diagnosis, team's memory must contain a list of symptoms to observe, the order of observations (when important), and the findings from the observations. In Figure 4(a), team's working memory during diagnosing is visualized as a puzzle board metaphor. To successfully perform a treatment, a team's memory must contain the diagnosis, selected treatment, tasks to implement the treatment, task parameters, and confirmation that each task has been completed. The lecture board metaphor in Figure 4(b) depicts a team's memory during treatment, containing parameters of the ordered tasks and their current status.

The metaphors of a team's working memory in Figure 4 helped us understand its importance in teamwork. In current practice, however, most of accrued information is stored in a trauma team's collective (or transactive) memory, rather than being externalized for reliable storage and easy access. In a chaotic and highly dynamic setting of the trauma bay, human working memory is susceptible to loss of the accrued facts. In addition, when the team leader queries other team members about past observations, the distributed cognition system effectively functions in System 2 mode, where central executive accesses the memory several times during rule application (Figure 3(b)). We use this model of teamwork in our work to highlight the importance of external representations and how the lack of such representations may lead to team errors.

5.3 Team Errors Predicted from the Model of Trauma Teamwork

ATLS is not a linear process; it has many branches that can be taken based on the results of previously matched rules. Analysis of activities in the observed resuscitations showed variation in task performance and sequence. The observed differences often did not represent errors in the conduct of ATLS, but rather acceptable variations within its framework. For example, intravenous access establishment, a part of ensuring adequate perfusion (C), was performed in parallel with the chest examination, a step for evaluating the adequacy of ventilation (B). Variations of this kind were chosen based on patient injuries, team experience and composition, or the team leader's skills. Others have found similar variations [Kahol et al. 2011; Klein et al. 2006]. While some variations may not be harmful, deviation from the management and treatment goals of ALTS have been shown to have an adverse effect [Clarke et al. 2000; Gruen et al. 2006]. We adopt the definition of *medical error* by the Institute of Medicine as "the failure of a planned action to be completed as intended or the use of a wrong plan to achieve a goal" [Kohn et al. 2000]. A plan (or rule) is considered wrong if it is likely to have an undesirable outcome. Our classification of "right" or "wrong" rules is based

Table I. Proposed Classification of Teamwork Errors

Error Type	Description
Communication error	• Failure to communicate information • Partial reports and partial orders
Vigilance error	Failure to intercept and prevent errors of other team members
Interpretation error	Incorrect or needlessly delayed diagnosis based on available information
Management error	Loss of track of progress for a multistep procedure

on domain expertise (codified by ATLS). Because trauma resuscitation is highly complex process with many unknowns, it is possible for a plan—that would otherwise be considered wrong by ATLS—to yield the intended outcome, but we deem its application an error, given the state-of-the-art.

It has been observed that experts mostly rely on automatic recognition (i.e., System 1), whereas novices rely on analytical thinking (i.e., System 2) [Klein 1998; Norman 2009]. Experiments in diagnostic reasoning have shown that System 1 thinking is about 10 times more effective in arriving at the correct diagnosis than System 2 [Norman 2009]. Both System 1 and System 2 are prone to errors, but in different ways.

In the distributed cognition system (Figure 4), errors in performance are mainly due to failures of communication or working memory. Table I summarizes the types of team errors that our teamwork model predicts. During evidence gathering and integration (Figure 4(a)), various team members collect patient information and communicate it to the decision maker who then integrates it and makes a decision. We observed that this process is subject to several types of errors. First, because trauma teams exchange information verbally, team errors can happen due to communication failures (*communication errors*). In Figure 4(a), a team member may find a piece of a puzzle but fail to report it to the team leader (failure to communicate). While trauma team members are required to call out their findings and status of their activities, our observations showed that they often failed to do so. Information loss can also occur because of ambient noise and parallel speech. We subdivided communication errors into failure to communicate information, and partial reports and partial orders. (A different subdivision, introduced by Singh et al. [2007], is based on failures in message transmission, message reception, and message acknowledgement.) Second, teamwork requires alertness for possible errors by other team members. A person may fail to verify the soundness or accuracy of received information before using it (*vigilance error*). For example, the pharmacist should check if the physician ordered a correct medication and the nurse should check if the pharmacist issued the same (Figure 4(b)).

Third, the team leader may err in interpreting available evidence (*interpretation error*) by failing to hypothesize appropriate new rules, or by waiting for strong cues rather than diagnosing using partial evidence or weak cues. To diagnose, the leader matches the symptoms specified by a rule against the observed facts stored in working memory. When a rule is successfully matched, its specified treatment is performed. Although trauma team operates mainly in System 1 mode of distributed cognition, we contend that it currently operates suboptimally. System 1 requires that all input facts are available *simultaneously* for central executive to perform pattern matching against the IF conditional. In reality, the trauma team acquires the facts sporadically and asynchronously. The team leader is susceptible to losing the accrued facts in a chaotic and highly dynamic setting of the trauma bay. Even if the facts are available somewhere in the team's collective memory, the leader must retrieve them sequentially (by verbally querying other team members), which interferes with the automatic pattern recognition of System 1. As a result, the team leader usually falls back on recognition of immediately available evidence and tends to neglect previously collected evidence.

To facilitate recognition-based thinking, it is necessary to externalize the team's working memory. The puzzle assembling metaphor in Figure 4(a) highlights the importance of having the partial evidence easily accessible (for System 1-based recognition). This metaphor also helps understand why the lack of such representation may lead to interpretation errors.

We can predict similar team errors during the treatment execution (Figure 4(b)), because this process also relies on working memory and communication. Communication errors occur when the leader gives an incomplete order or when a team member fails to report completion of a treatment step. Vigilance errors occur when team members uncritically accept erroneous information from others and use it in their tasks. *Management errors*, a new type of team errors found in treatment execution, occur when the team leader loses track of the progress of current activities. Additionally, other team members may have inadequate information about the parameters specified by the leader for their tasks. Management errors are particularly pronounced in multistep procedures, such as the administration of medications or fluids. Again, the lecture board metaphor in Figure 4(b) highlights the importance of externally displayed information about teamwork. In current practice, a team's collective memory does not effectively store this information nor makes it easily accessible.

We also observed team members interfering with each other's work (*concurrency error*). In one event, the orthopedic resident repeatedly lifted the patient's arm while the team leader was working on a chest tube insertion on the same side. This interference prompted the attending physician to ask the orthopedist to defer his examination. Errors in technique, such as improper insertion of a tube into the bladder to provide continuous urinary drainage or improper rolling of the patient, were observed as well. Both procedures require coordination of multiple people and their skills. In this work, we focus on information-based errors because we want to identify critical information structures that need externalization. Concurrency errors and errors in technique are not considered here, for these are failures of coordination and can be mitigated only by training.

We next present findings from the analysis of 18 actual resuscitations conducted to verify our taxonomy of team errors (Table I).

6. FINDINGS

To illustrate and discuss team errors in actual events, it is useful to have a case example that shows trauma team activities during resuscitation. The example narrative is from event #15 that involved a patient injured in a motor vehicle crash, who sustained internal bleeding from a severe pelvic fracture, and experienced bradycardia (heart rate drop) and hypotension (low blood pressure) during transport. This event highlights the challenges faced by trauma teams when evaluating patients with internal injuries not apparent on external examination. Because this event overlapped with three other simultaneous resuscitations, it also highlights the challenge of managing critically injured patients when more than one patient is being evaluated. After presenting the case example, we describe and classify team errors observed during this event and provide examples from the remaining 17 events to reinforce our findings and illustrate variations in the data.

6.1 A Case Example

The patient arrived by air and was brought to the trauma bay by the emergency medical services (EMS) paramedics, a junior resident, and the primary nurse. The team leader was in the trauma bay waiting for the patient and did not receive a report from the EMS crew on the helipad, as is customary. Information about patient status en route was critical to the team because the patient's heart rate (HR) and blood pressure (BP) dropped significantly during transport. The EMS crew was considering administering emergency medications for low HR and BP. Because they were close to the hospital, they postponed administration of these medications until arrival to the trauma bay.

The patient arrived to the trauma bay with an oxygen mask and a cervical collar. Based on this information, the team concluded that the patient had a patent airway (step A of ATLS). At the same time, the primary nurse stated the emergency medication names and handed syringes over to the EMS paramedic, who then passed them on to a second nurse (Nurse2) to administer them. After overhearing the medication names, the team leader asked the team when the last dose was administered. Without waiting for an answer, the leader proceeded with evaluation and started examining the patient's chest and lung sounds (B). Instead of giving a direct answer to the team leader, the paramedic started explaining why the patient needed emergency medications. The second nurse remained quiet, although it appeared that he was currently administering the medications. (The team leader's comments later in the event showed that he believed, correctly, that the emergency medications had not been administered.)

At this time, the junior resident reported the patient's pulses (C), and the team leader reported findings from his chest examination. After gathering pieces of information and evaluating the patient for two minutes, the team leader asked, "Can somebody please repeat the story!" The junior resident who heard the report on the helipad debriefed him: "[Age] year old male, motor vehicle crash, initially hypertensive, BP 165 on scene, hypotensive in the 60s."

While listening to the report, the team leader moved onto the examination of pupils, which is primarily used for identifying neurological injuries (D). Three minutes into the resuscitation, the team leader diagnosed unequal pupils, "Pupils dilated on the left, 4, on the right 2," and continued with routine evaluation inquiring, "Do we have x-ray here?" At this time, the primary nurse was setting up an additional intravenous access and drawing blood, and the technicians were assisting with IV fluid administration. Several other team members inquired about the presence of the orthopedic resident who had not yet arrived to the trauma bay. The team's beepers sounded shortly thereafter, signaling that two additional trauma patients were arriving.

The team leader observed unequal pupils, a sign of a potential head injury, but did not visibly alter his evaluation process. Distractions with other aspects of the patient's care, as well as distractions external to the room, likely contributed to the task sequence chosen by the team leader. The announcement of other arriving patients increased the urgency of evaluating and managing the patient.

Although in a hurry to obtain the needed x-rays, the leader decided to wait until the primary nurse completed his tasks. Around six minutes into the event, the attending physician entered the room for the first time and asked for an update on the patient. The team leader repeated the EMS report and evaluation results, including the abnormal pupils finding. Despite hearing about abnormal pupils, the attending decided to proceed with routine evaluation steps, and the patient was prepared for rolling on the side to evaluate for external injuries (E).

When a pelvic fracture is observed or suspected, a rectal examination serves as a supplementary diagnostic evaluation. Because the patient is turned on a side to evaluate for external injuries, a rectal examination is usually done in step E. Upon finishing the back examination, the junior resident performed a rectal examination at about 8 minutes into the process, but did not report the findings. The orthopedist arrived shortly thereafter, just as the team was ready to take x-rays. He examined the pelvis quickly by compressing it externally, but also did not report his findings. The

Table II. Excerpt from Event #15 after the Patient's Blood Pressure Suddenly Dropped (some lines are omitted).

Line #	Time	Actor	Action	Subject	Communication
351	16′3″	Attending	(talks to	TEAM)	Put him back on the regular monitor!
352		Nurse2	(pumps a fluid bag)		
353		Primary nurse	(talks to	Nurse3)	We are taking him off of the portable monitor, we are not going anywhere!
354		Nurse2	(talks to	TEAM)	He still got pulse.
355		Tech2	(starts connecting PTN to regular monitor)		
356		Tech1	(enters room, talks to	Nurse3)	(Name), I got your (unintelligible)
357		Nurse3	(pumping fluid, turns to	Tech1)	No, back to the regular monitor!
358		Tech1	(talks to	TEAM)	That's it, I got another patient...
359	16′24″	Team leader	(talks to	Tech1)	Blood pressure dropped!
360		Attending	(talks to	TEAM)	Did we get his HemoCue?
367		Tech1	(talks to	Attending)	(unintelligible)
368		Attending	(leaves the room)		
371		Attending	(enters room, rolling in FAST machine, talks to	TEAM)	Fluids running wide in?
372		Nurse2	(talks to	Attending)	Yes.
373		Team leader	(approaches x-ray station, pings for the x-rays)		
374		Attending	(talks to	TEAM)	How many IVs?
375		Nurse2	(talks to	Attending)	He's got three IVs, two 16 and an 18.
376		Attending	(talks to	TEAM)	And fluids run through all of them?
377	17′6″	Nurse2	(talks to	Attending)	Ah, I am just getting fluids for the third one and I'll hang it right now for you.
378		Nurse3	(hands a fluid bag to	Tech2)	Hang it up there.
406	18′55″	Attending	(talks to	TEAM)	(unintelligible – pressure?), have we given any meds?
407		Nurse3	(talks to	Attending)	No meds(?) have been given, that's why they didn't give anything...
408		Tech2	(talks to	TEAM)	BP 71 over 41
409		Attending	(talks to	TEAM)	How much fluids running in total?
410		Nurse2	(pumps the bag, counts talks to	Attending)	One, two, three, four, 2 liters... I've got one down over there... 2 liters so far, we're working on 5
411	19′19″	Attending	(uncovers PTN, talks to	TEAM)	I am not seeing any indication of where he could be bleeding.

team then recorded the x-rays and began preparing the patient for transport to the CT scan while waiting for x-rays to be processed.

Seven minutes later, the patient was stabilized, switched to a portable vital signs monitor, and readied for transport to the CT scan. Suddenly, the patient's blood pressure dropped to a critical value. At this time, the team leader was focusing on the patient's x-rays at a station in the corner of the room. The vital signs monitor sounded an audible alert signaling the patient's low blood pressure. This alarm, however, did not refocus the team's attention to the patient's changing status. After a minute during which no team member responded, the respiratory therapist walked in to the room, immediately noticed that the alarm was sounding, and asked, "Is he OK?" The primary nurse approached the monitor, looked at it, and shouted, "(expletive)!... 65 over 40! Open the fluid!" The team leader was still focused on the patient's x-rays and did not immediately respond to this change. At this point, the attending physician came back from managing another trauma patient. The primary nurse now

Table III. Frequency and Averages of Team Errors for 18 Resuscitation Events.

Error Type	Event Number																		Avg
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Communication																			
• Failure to communicate	7	8	5	5	4	2	8	8	5	7	8	8	3	10	7	7	2	3	5.9
• Partial report/order	2	1	1	2	0	0	1	1	0	0	0	1	0	0	2	1	2	0	0.77
Vigilance	0	0	2	2	2	1	0	0	0	0	1	0	0	0	2	0	3	4	0.94
Interpretation	0	1	1	0	2	0	0	0	0	1	0	1	0	0	2	1	3	3	0.83
Management	0	0	2	1	0	0	0	1	0	0	1	0	0	1	1	1	1	0	0.5

addressed the attending physician directly, “BP 65 over 40 doc!” The attending immediately started giving orders, “Put him back on the regular monitor!” (Table II). The team leader eventually became aware of the change in patient status and assisted with direct patient care. The attending was not able to diagnose the cause of the low blood pressure (“I am not seeing any indication of where he could be bleeding”) until pelvic x-rays at 20 min post admission showed a severe pelvic fracture that had led to internal bleeding. The presence of this injury and persistent low blood pressure prompted the team leader to order a blood transfusion. At 25’ 44” after the patient’s arrival, the patient was transported to the radiology department for a CT scan.

Although successful, the preceding trauma resuscitation revealed problematic aspects of treating severely injured patients. The team made several errors and did not acknowledge and react to the potential signs of internal bleeding. We use errors from this case as primary examples of real-world team errors and we supplement them by examples from the remaining 17 resuscitation events.

6.2 Applying Team Error Classification Scheme to Observed Problems

We next apply our classification scheme to problems observed in actual resuscitations and provide examples from those events (summarized in Table III).

6.2.1 Communication Errors. Communication errors occur due to ambient noise, mutual interference, misunderstanding and information loss. Information can be lost not only in transmission but also if partially reported or not reported by the observer. Communicating observed evidence makes it possible for the team leader to correctly diagnose the patient’s injury. In addition, communicating information makes it part of collective memory and increases the efficiency in decision making by averting repeated inquiries. Any of the communications between the actors in Figure 4 are subject to errors. We identified several types of communication errors, including failure to communicate critical patient information, partial orders, and partial reports.

Failure to Communicate Information. A commonly observed communication error is failure to communicate information [Clarke et al. 2000]. Trauma team members are required to report aloud the status of their activities, such as completion of a task or a test finding. Reporting helps the team maintain situation awareness about current activities in the trauma bay. The patient status assessments and diagnoses made by the team leader are important for others to hear so they can anticipate and prepare for their tasks. The nurse recorder relies on verbal reports to document patient encounter during resuscitation [Sarcevic 2010]. Problems arise when team members fail to report the status of their activities or test findings, which results in a team’s incomplete situation awareness and knowledge gaps. To fill in these gaps, team members query each other, which in turn results in redundant questions, delays, and increased levels of noise. In the case example, the orthopedic and junior residents failed to report findings from pelvic and rectal examinations, respectively. Failures to communicate examination findings (e.g., airway, neurological, and abdominal exams) were observed in all resuscitation events. Several possible explanations for these failures emerged from discussion with medical experts on our research team: (a) residents might have forgotten to report their findings; (b) if they found everything normal, they might have decided that reporting their findings would contribute no new information and would only add to the ambient noise; or, (c) residents might have considered their findings uncertain and hesitated reporting to the team.

Another example of this error type is the failure to report vital signs. The vital signs display is positioned to the side of the patient's bed, making it difficult to view. The technician and primary nurse are assigned to call out the patient's vitals periodically for everyone, but they often forget to check the monitor. Even when the vitals are called out, most often only one or two parameters are reported. The recorder, who is positioned at the other end of the room, has trouble hearing vital signs reports and often asks for this data to be repeated. If no vitals are reported for a long period, the team leader, attending physician or nurse recorder may verbally prompt for their reading. Failures to report vital signs were often observed throughout the study. Consider an episode from event #2.

> At about 5 minutes into the evaluation, the patient's blood pressure was still unknown. The technician was trying to obtain automatic blood pressure, but with no success. He decided to measure it manually. Two minutes later, the first blood pressure measurement was reported. The recorder missed the report while talking to an EMS paramedic. The attending physician noticed this and relayed the message to the recorder, who finally acknowledged it. Shortly thereafter, the technician reported new blood pressure. The blood pressure was dropping and the attending physician relayed this message to the recorder again. The team leader ordered a bag of fluid. Five minutes later, the team leader requested, "Can we get another blood pressure?" The technician responded, "I'll give it to you right now!" and started measuring blood pressure manually.

The technician needed a verbal reminder to obtain a new measurement, which shows the lack of anticipatory reporting and repeated requests for critical patient information.

In addition to unreported examination findings and vital signs, team members often failed to communicate other types of information including patient medical history or treatments, such as administered medications. In our case example, the nurse who appeared to be administering emergency medications at the start of the resuscitation did not report whether he had actually done it. This failure resulted in uncertainty about administration of the medications, which was not resolved until later in the resuscitation.

Most of the failures to communicate information were about examination findings, followed by failures to communicate information about treatment (e.g., administered medications) or measurement (e.g., vital signs).

Partial Reports and Partial Orders. We also observed communication breakdowns when a team member provided a partial report or gave a partial order. In our case example, the nurse recorder and the primary nurse became confused about the emergency medications that were administered en route partly because the initial EMS report did not mention all administered medications. Fortunately, the EMS paramedic was present in the trauma bay when this information was needed, and was able to respond to the nurses' inquiries. In the same resuscitation, the team leader ordered blood transfusion but did not specify other details needed for transfusion, which prompted the primary nurse to clarify this order. Partial reports and partial orders mostly resulted in increased communication exchanges, as illustrated in the following example from event #11.

> At about eight minutes post admission, the technician obtained a new blood pressure measurement. The patient's blood pressure was dropping. The team leader ordered fluid, "Get her fluids going" but did not specify the volume. The primary nurse inquired if the team leader wanted two or only one fluid bags. Moments later, the technician reported the size of an intravenous access gauge to the nurse recorder but did not specify location. Shortly thereafter, the recorder asked the technician, "Is the IV in the right or the left?"

6.2.2 Vigilance Errors. Trauma resuscitation is a highly team-dependent process where subsequent tasks use the results of previous activities. Team members pass on information and physical items, such as medications, requiring each individual to be alert for potential errors. When a team member accepts erroneous input uncritically and uses it in his or her task, it is a vigilance error. We consider these as team errors because they signify a collective failure. For example, when the anesthesiologist orders a medication to paralyze the patient, the pharmacist should check for its appropriateness and patient's allergies, and the nurse responsible for administration should verify that the type and dosage received from the pharmacist are correct. Alertness for others' errors plays a key role in preventing drug-administering errors in other hospital units [Leape et al. 1995].

Vigilance errors in trauma resuscitation can dovetail with partial-order communication errors, when the message recipient proceeds with partial information rather than requesting clarification. In one event, the team leader ordered antibiotic but did not specify the dosage. The recorder understood this request to be a standard dosage (two grams) and asked the primary nurse to prepare two grams. The attending physician overheard the recorder's order and corrected it, "One gram is enough."

In another example from event #7, we observed the primary nurse verifying the medication order several times.

> The patient was screaming as the leader proceeded with his evaluation. The recorder suggested giving morphine: "Do we have any morphine?" Primary nurse thought this was a good idea ("Yeah, I think that would be a good idea.") and looked at the team leader. The leader quickly glanced at the vital signs monitor and ordered: "We'll give 2 mg of morphine, first check the blood pressure, if it is okay, we'll give it." Shortly after, the leader ordered two additional medications: "We need Ancef and tetanus!" Upon hearing this request, the primary nurse immediately clarified: "No morphine?" After waiting for a few moments, she asked again: "Doc, do we get some morphine?" The orthopedic resident overheard the communication and responded to the nurse: "Yes, she said morphine, check the pressure and then give some morphine."

During informal interviews, trauma team members often stated that all members bear responsibility to ensure team's adherence to the resuscitation protocol. If a team member notices a skipped evaluation step, they should alert the others. For example, in event #4, the leader performed log roll (step 'E') before the neurological assessment (step 'D'), which was a deviation from the protocol. Upon completing the log roll, the nurse recorder requested information about the patient's pupils, which prompted the leader to do step D and report findings. Senior members of the team, such as attending physicians, fellows, and senior nurses are expected to ensure that the order of activities follows protocol, unless patient status dictates a need for deviation.

6.2.3 Interpretation Errors. Interpretation errors occur when team reaches an incorrect or unnecessarily delayed diagnosis based on the available information. Although also found in individual work, interpretation errors appear in teamwork for different reasons. First, accumulated communication errors may lead to interpretation errors. When team members fail to communicate observed data to the team leader, he or she may make an error if diagnosing with incorrect or insufficient information. In our case example, both the orthopedist and junior resident failed to report findings of their assessments. The nurse who appeared to be administering emergency medications at the beginning of the event also did not report whether or not he administered medications. Second, we found that decision makers rely only on strong cues and do not react to weak evidence. In the case example, the team leader observed unequal pupils, a signal of a potential injury, but did not visibly alter his evaluation process. In other words, when viewed from distributed cognition perspective, the central executive did not generate diagnostic hypotheses because there were no visible signs of initiating further data acquisition to confirm or reject those hypotheses. Only after reviewing the x-rays relatively late in the process, the team confirmed internal bleeding and localized it. This finding relates to the physician's tendency to over-rely on expensive and unnecessary diagnostic tests [Bordage 1999]. A similar situation appeared in event #17 in which a severely injured patient arrived with decompressed left chest. The team suspected internal bleeding in the left chest and inserted a chest tube into the patient's left side. Only after viewing the x-rays at about 30 minutes into the resuscitation, the team realized that internal bleeding was in the right chest and rushed to insert the chest tube on the patient's right side. This team also had difficulty obtaining the patient vital signs. The problem of obtaining and the method of measuring vital signs were extensively discussed by the team. Rather than diagnosing this problem as a sign of a potential injury, the team believed the equipment was malfunctioning.

In addition to relying on strong cues only, the decision maker has problems with integrating multiple weak, but relevant, cues because they are reported at different times and have to be memorized and later recalled. In our case example, the facts needed for executing the rule for detecting internal bleeding became available as follows: en route blood pressure drop and heart rate drop; rectal examination at 7' 44"; pelvic rock examination at 8' 30"; significant decrease in blood pressure at about 15'; and x-rays findings at 20'. Similarly, the facts needed for diagnosing internal bleeding on the patient's right side in event #17 became available with many minutes passing between the observations: en route rapid heart rate and blood oxygen deficiency; en route left-side chest decompression; repeated observations of equal breath sounds reported within the first 15 minutes; first blood pressure measurement at about 20'; results from the first chest tube insertion at about 25'; and x-rays findings at 30'.

An important question then is why trauma teams appear to miss several cues during the primary survey that suggest a serious internal injury. Although rapid, the primary survey can uncover key cues that the team can use to diagnose internal injuries, without relying on time-consuming and expensive imaging techniques. One possible explanation is that the primary survey in most resuscitation events reveals no critical injuries, leading the team to become conditioned to expect normal findings during this evaluation phase. We further discuss this issue in Section 7.

We observed 15 interpretation errors in 9 events, most of them occurring in the three events (#15, #17, #18) that involved critically injured patients (Table III). The remaining 9 events had no interpretation errors. Every time we observed the team leader not visibly acting upon a weak cue or otherwise not using the evidence when diagnosing, we counted this incident as an interpretation error. Although interpretation errors were observed in routine cases, they were less salient as they had low potential impact on the patient.

6.2.4 Management Errors. Management errors occur when the supervising team members lose track of the progress of multistep procedures such as the administration of medications or fluids. An individual error of losing track of one's own activities differs from a management error because the latter relates to the failure to monitor what others are doing. When a person is executing a multistep procedure alone, it is relatively easy to keep track of the current step. When multiple people are involved, it is hard to track the progress, especially if the supervisor is also busy with other tasks. In this case, some team members may know the current step in an ongoing process, but the supervisor may not know it. As the team leader needs to know the current status of individual tasks, the team members completing those tasks need to know task parameters, such as medication dosages or tube sizes.

In the case example, we observed that the team had difficulty monitoring the administration of emergency medications at the beginning of the resuscitation. Similarly, in event #3, the patient's airway started to deteriorate and the team decided to proceed with endotracheal intubation (a procedure in which a tube is inserted into the trachea to assist with the patient's breathing). The anesthesiologist ordered a medication needed to paralyze the patient. He needed it done quickly and, he inquired about it eight times over the period of three and a half minutes. It appeared that the anesthesiologist was not sure where the pharmacist and the primary nurse were in the six-step process required for administering both medications, which resulted in repeated questions.

Another multistep procedure that requires monitoring is the administration of intravenous fluid. This procedure consists of the following steps: ordering fluid, retrieving the bag of fluid from the cabinet, setting up the bag, starting the flow of fluid, and periodic monitoring of the infusion rate. Difficulty with tracking fluid administration was observed in three events, including the case example (see Table II, Lines 371–410). Management errors can be critical, but are more likely to be caught than interpretation errors because progress status can be determined by verbal communication.

7. DISCUSSION OF TEAM ERRORS AND OBSERVED PROBLEMS

Trauma teams face significant challenges when performing the multistep evaluation and treatment procedures required by ATLS. Communication errors are most common. They slow down the process—team members have to request information, which interrupts their work—and may contribute to other types of errors [Clarke et al. 2000]. Rule application depicted in Figure 4 requires a great deal of communication for reporting the results of observations and interventions, as well as for assigning tasks, providing feedback or retrieving information. It may appear then that most of the observed team errors are due to communication errors. However, we believe that the cause of most team errors, including communication errors, is the way in which a team's working memory currently operates, relying on collective memory and verbal exchanges. If a team's working memory were externalized as in the metaphors of Figure 4, the need for communication would be reduced and many communicative exchanges would be unnecessary, resulting in fewer occurrences of communication and other errors.

According to domain experts on our research team, interpretation errors are the most serious type of team error that we identified. Interpretation errors (incorrect diagnosis) cannot be quickly resolved with a follow-up query. Instead, these errors require generating a new set of diagnostic hypotheses and gathering new evidence, which is both cognitively demanding and time consuming, and may have serious consequences.

Our observations showed that during resuscitation, there is a lack of longitudinal tracking and integration of information. Although resuscitations are relatively short, the team is exposed to large quantities of situational information. Our transcripts contain on average 429 lines of communications and actions for an average 23-minute resuscitation, which yields about 17 discernable actions per minute of resuscitation. As a result of this information overload, team members often forget the details of performed tasks. We found that trauma teams make judgments based upon facts available immediately, and forget or assign lesser importance to data obtained earlier. This finding is well known from general research in decision-making under uncertainty [Hastie and Dawes 2001].

Earlier in the article (Section 6.2), we observed that trauma teams ignore important cues during the primary survey. Although team members observed and successfully communicated the cues needed to make the correct diagnosis, they did not use these findings to properly apply the rules. In our case example, there were no visible instances of physicians using weak cues in the diagnostic process. Using weak cues would have visibly affected their subsequent actions, but it did not. They might have used weak cues at the time when the correct diagnosis was made and appropriate treatments were selected. By this time, x-rays showing the bleeding (a strong cue) eventually became available, making any previously observed weak cues superfluous. If taken individually, the symptoms in the IF conditional of an expert rule are often insufficient to derive a conclusive diagnosis. When properly tracked and integrated, these cues may offer strong evidence for a diagnosis. People have difficulty integrating multiple cues in decision making even if all cues are simultaneously presented [Hastie and Dawes 2001]. The sporadic occurrence of cues increases the difficulty of the integration task: a large amount of situational information needs to be held in memory and a large amount of domain knowledge needs to be recalled at the time a diagnosis is attempted. In a distributed cognitive system, the difficulty is further exacerbated by the fact that situational information is distributed across team members (or stored in a team's collective memory) and needs to be verbally recalled during diagnostic reasoning. Because this process depends on error-prone verbal communication, it often leads to poor data integration, that is, interpretation errors.

Our findings suggest that trauma teams have difficulty integrating weak cues, especially when different team members obtain these cues at different times. Given that weak cues become available much sooner than strong cues (e.g., x-ray findings), they could help arriving at the diagnosis faster. In our case example, the weak cues did not shorten the time to reach the diagnosis. In most of the observed events, evaluation proceeded in a generic manner after obtaining a weak cue. This finding implies that weak cues were often not used for diagnosing or to initiate additional evidence gathering. Also, there were no visible signs that earlier evidence was acted upon later during the event. According to domain experts on our research team, the diagnoses made or requests for additional tests were based almost exclusively on the immediate evidence.

Based on our model of teamwork, we propose that the trauma team represents a team cognition system that is functioning suboptimally. In theory, an optimal decision system would use all available evidence to arrive at the diagnoses by probabilistic integration of the evidence [Oaksford and Chater 2007]. In practice, the trauma team unintentionally ignores weak evidence and relies only on strong cues. The decision maker has problems with integrating multiple weak-but-relevant cues, because they become available at different times and have to be memorized and later recalled. Although experts prefer recognition-based System 1 thinking, memory recall from either individual or collective memory enforces System 2 mode of thinking, which relies on sequential data accrual and inductive inference. Still, because previously observed data are not easily accessible when needed, the team leader resorts to System 1 thinking using only immediately available data. When used in such manner, weak cues are insufficient for diagnosing and reliance on strong cues becomes inevitable. Our teamwork model explains how different error types are interrelated when collaborative teams execute expert rules; it shows how each team member may be doing their work correctly, but because they are relying on inefficient collective working memory, they are failing at the team level.

Our analysis of 18 actual resuscitations confirms our model predictions about four types of team errors. Only a few instances of team errors remained that did not fit into our taxonomy. For example, when two team members obtain conflicting observations using different methods (e.g., blood pressure measured manually vs. automatically) but do not try to resolve the conflict may comprise more than a vigilance error. In another example, the leader noticed a team member poorly performing a task, so he stepped in, leaving the team without leadership for an extended period. Another type of team error occurs when, as in our case example, the entire team fails to acknowledge the auditory alerts from the vital signs monitor for almost a minute, which is a critical delay for an unstable patient. This error is not a vigilance error because there is no transfer of information among team members. It could, however, be classified as a fixation error [Reason 1990], potentially caused by habituation to ambient sounds, or by a perception that the patient was stable and ready to move to the CT scan. Studies of auditory alarms in medical settings by Xiao and colleagues [Xiao and Seagull 1999; Xiao et al. 2004] revealed a diverse set of factors that increase the probability of not responding to alarms, including the problem of interpreting the significance of a state change.

We are now working on further analysis and extensions of our teamwork model to account for the error types that do not fit into our current classification scheme. We are also considering other models of cognition, such as Klein's RPD model [Klein et al. 1993].

Trauma resuscitation teamwork, despite its complexity, could be viewed as an easier problem to represent compared to an unconstrained team activity. The roles are relatively constrained, the physical artifacts are reasonably distinct, there is a clear locus of activity (the patient), and the process is governed by a well-defined protocol. It may appear that these characteristics of trauma teamwork limit applicability of our teamwork model and error scheme to other domains. To our knowledge, most safety-critical teams are highly structured, and their work is governed by specialized rule-based protocols. Hence, we believe that our results generalize to other dynamic, safety- and time-critical settings.

8. OPPORTUNITIES FOR COMPUTERIZED SUPPORT

Based on the results from this study, we can identify opportunities for improving trauma teamwork and mitigating or reducing errors. Various approaches can be pursued. For example, some vigilance errors can be reduced by applying Crew Resource Management (CRM) approach [Helmreich et al. 1999; Salas et al. 2006]. Here we focus on approaches that rely on information technology. Decision making in trauma resuscitation currently relies on human working memory. This feature of trauma teamwork is different from other critical domains, where situational information is extensively externalized to information artifacts. Our study showed that a relatively low degree of information externalization impairs distributed cognition in the trauma bay.

We identified three potential approaches for computerized support in safety-critical settings characterized by rapid information acquisition and processing.

(1) Information display for improved situation awareness
(2) Automatic suggestion for the subsequent actions
(3) Automatic diagnosis

All three approaches require capturing detailed situational information, but they use it in different ways. The first approach makes critical information accessible to the team to support their activities. The second approach tracks the resuscitation progress and helps ensure that important evaluation steps are not skipped or performed in wrong order. This second approach can be thought of as an automated checklist to ensure quality and safety of resuscitation. Fitzgerald et al. [2011] have shown that such systems have potential to improve trauma care. Based on manual entry of situational information and a limited set of trauma injuries and tasks, they developed a system that delivers computer-generated intervention prompts, requiring action from the trauma team. The third approach uses artificial intelligence techniques for automatic diagnosing and treatment recommendation [Gertner and Webber 1998]. We believe that the first approach is currently the most promising because it focuses on aiding information access and recognition-based thinking, and leaves decision making to the trauma team. The second approach helps ensure correctness and completeness of evaluation steps, but does not address making the accrued information accessible for diagnostic reasoning. The display approach can help along each step and benefit all team members, unlike the last two approaches, which mainly focus on aiding the team leader's work. Our observations described earlier show that all team members make errors and could benefit from technology support. Even if we developed an artificially intelligent decision-support system, it is the medical providers who do the trauma care, so technology should support their work. The second and third approaches focus on supervising and directing teamwork, instead of assisting it.

As we emphasized earlier, trauma teams mainly rely on collective memory and verbal communication for information access; there are no mechanisms by which patient information is currently accrued to allow for integration and analysis. Two specific recommendations emerged from our study.

(1) Improve the functioning of a team's working memory by externalizing situational information.
(2) Make situational information easily accessible using wall displays or other modalities.

Making situational information easily accessible would improve System 1 thinking by enabling pattern matching of IF conditionals on all situational information accrued up to the moment. Reduced load on human working memory would aid System 2 thinking where needed because workers' expertise is insufficient for System 1 pattern matching. Information externalization and display would also reduce reliance on verbal communication and help avoid associated communication errors. This intervention would result in improved distributed cognition in the trauma bay, potentially making trauma teams more efficient and less error prone.

A key problem that needs to be addressed by a technology solution for externalizing situational information is automatic capture and display of situational information in real time (Figure 5). The current mechanisms for externalizing information in trauma bay (described in Section 3.2) cover only a fraction of information needed for efficient decision making. There are examples of automatic capturing and displaying

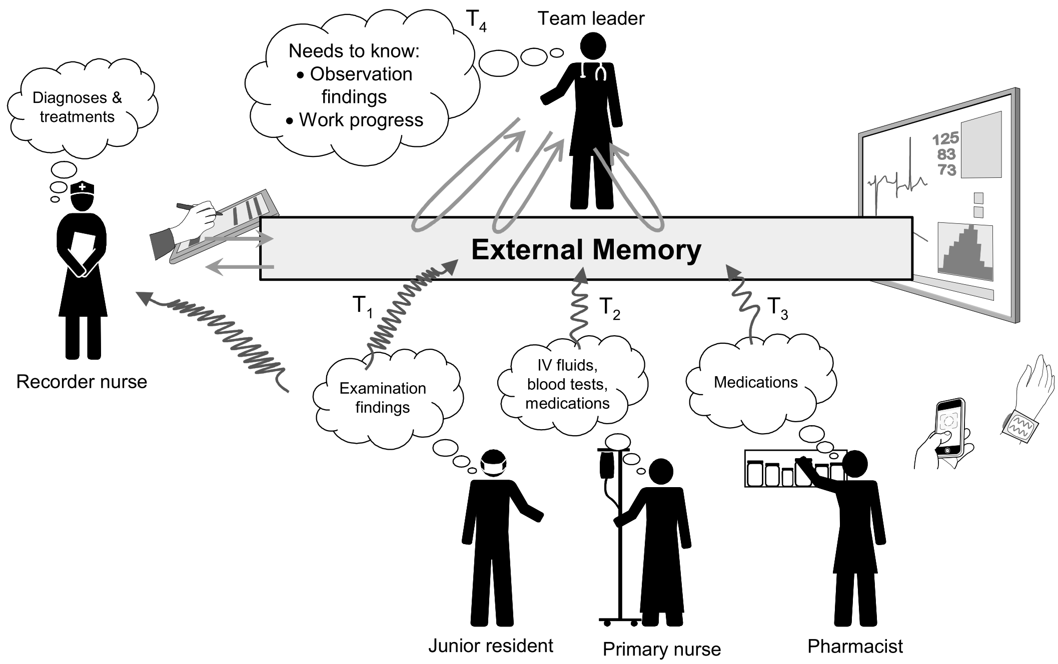

Fig. 5. Towards distributed cognition in trauma resuscitation.

situational information in other medical and nonmedical domains. Most research on developing technology for situation awareness so far has been focused on settings where workers interact with engineered systems, such as airplane cockpits or nuclear power plant control rooms. In these settings, technology mediates interaction with the work domain. In contrast, during trauma resuscitation, the workers primarily interact with the patient and various instruments. Interaction with computers may be considered a distraction in this domain, calling for a careful approach to the design of the entire socio-technical system.

In other hospital units, where there is no time pressure, technology has been employed to digitally capture every communication in the process of ordering and administering medications, which has led to reduction in human errors [Leape et al. 1995]. In trauma resuscitation, communication is primarily verbal and only partially recorded on a paper flowsheet. The nurse recorder documents physicians' orders and examinations findings, but not the individual steps of the order execution. Management errors that we observed suggest capturing the process in real time and visualizing it to aid rapid tracking and integration. Process information could be automatically captured using sensor networks and RFID technology. Bardram and colleagues developed systems that turned the operating room into a context-sensitive environment in which the system monitors the room and provides timely information to clinicians [Bardram and Norskov 2008; Bardram 2009]. These approaches are difficult to implement in the trauma bay, which is crowded and fast-paced, and where little time is left for computer interaction. Automatic capture of teamwork activities appears to be the most plausible solution, but due to the complexity of the trauma bay setting, significant advances in algorithms for object tracking and activity recognition are required.

A key challenge in designing information technology for trauma resuscitation is to prioritize the information that needs to be externalized. Trauma teams manage large quantities of information about patient status and the team's current activities over the course of resuscitation. Based on our findings, we argue that the two most critical information structures in trauma teamwork include: (1) evidence accrued up to the present time; and (2) procedure steps that are successfully completed up to the present time. The puzzle board and the lecture board in Figure 4 symbolize these two information structures, respectively. To define specific information items that need to be displayed as part of these information structures, we will rely on our previous work. By analyzing communication among trauma team members, Sarcevic and Burd [2008] determined the most frequently sought information types during resuscitation. Furthermore, in a study of information handover between EMS paramedics and trauma teams, Sarcevic and Burd [2009] examined the types of information requested during and after information handover. These studies revealed the frequency and times at which specific patient information was needed. The remaining challenge is how to design the display for easy information access and efficient absorption, given the urgency of the situation.

Rather than proposing novel technology designs for externalizing needed information, our goal in this article was to identify team errors as well as critical information structures that require digitization to reduce those errors. One might expect that various types of displays could help externalize information held in individual working memories. Some information could be captured automatically (e.g., from vital signs instruments), but other information would likely need to be entered manually by team members (e.g., findings from physical examination). Entering information manually requires careful interface design and tasking specific team members with information entry, which is part of our ongoing research.

9. CONCLUSION

In this article, we provided an empirical understanding of team errors in time- and safety- critical setting of the trauma bay. To identify and explain teamwork errors, some of which were previously unknown, we proposed a model of trauma teamwork. We then illustrated problematic aspects of trauma resuscitation using one critical event as the main case example and complemented this discussion with examples from additional 17 resuscitation events.

Using ethnographic techniques and domain expertise, and guided by our model of team mind, we identified four types of errors that are unique to teamwork in trauma resuscitation domain: (1) *communication errors*, due to information loss; (2) *vigilance errors*, due to failing to intercept and prevent others' errors; (3) *interpretation errors*, due to the effect of sporadic, asynchronous data gathering and the current mode of collective memory operation on diagnostic reasoning; and (4) *management errors*, due to the team leader losing track of the progress of multistep procedures. All of these errors affected decision making. In addition to identifying team errors, we also provided explanations for their causes. We concluded that the key role of technology would be to externalize the situational information for reliable storage and easy access. The two most critical information structures in trauma teamwork that need externalization include: (1) evidence gathered up to the present; and (2) procedure steps that were successfully completed up to the present. The outcomes of this research can be used to inform the design of computer systems to support the work of high-reliability teams in various safety-critical settings.

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