Understanding Visual Attention of Teams in Dynamic Medical Settings through Vital Signs Monitor Use

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ABSTRACT

The purpose of this study was to understand how vital signs monitors support teamwork during trauma resuscitation—the fast-paced and information-rich process of stabilizing critically injured patients. We analyzed 12 videos of simulated resuscitations to characterize trauma team monitor use. To structure our observations, we adopted the feedback loop concept. Our results showed that the monitor was used frequently, especially by team leaders and anesthesiologists. We identified three patterns of monitor use: (i) periods with a low frequency of short looks (glances) to maintain overall process awareness; (ii) periods with a medium frequency of long looks (scrutiny) to monitor trends in patient status; and (iii) peaks with a high frequency of glances to maintain attention on both the patient and monitor during critical tasks. Approximately 75% of looks were 3 seconds or shorter, but many looks (25%) ranged between 3 and 26 seconds. Our results have implications for improving displays by presenting the status of the patient's physiological systems and team activities.

Author Keywords

Visual attention; information behavior; video analysis; health informatics; trauma resuscitation; feedback loop.

ACM Classification Keywords

H.5.3 [Groups & Organization Interfaces]: Collaborative Computing, Computer-Supported Cooperative Work, Organizational Design; K.4.3 [Organizational Impacts]: Computer-Supported Collaborative Work

General Terms

Design; Human Factors

INTRODUCTION

Trauma resuscitation is a complex, dynamic, and safety-critical process in which multidisciplinary medical teams treat critically-ill patients early after injury. Although seeing and examining the patient already provides important information, monitoring patient status using the vital signs monitor is essential for determining indications for and responses to life-saving treatments. The vital signs monitor, however, provides limited contextual information about patient status, team activities, treatments and outcomes. To obtain and interpret contextual information about the patient, past and current activities, administered treatments and outcomes, as well as pending tasks, team members mainly rely on verbal and non-verbal communication. Although communication is essential for team situation awareness and ensuring safe patient care, information reported verbally is often inaccurately transmitted or inaudible [4]. Poor information sharing has been observed even among experienced trauma teams, resulting in procedural errors, inefficiency, and delays [27]. In an environment where providers' attention is limited, it is important to assess the feasibility of supplementing existing displays with information that supports teamwork and decision making. In this paper, we examine the use of the vital signs monitor to derive design requirements for additional information displays.

In the visual attention literature, there are many studies of gaze patterns across a range of tasks, including car driving [21], laparoscopic surgery [17], and information search [12]. By using eye-tracking equipment, these studies examined search patterns and dwell times of individual participants engaged in visual problem-solving tasks while looking at a single display. A recent study of the distribution of visual attention in anesthesia providers has shown that 30% of visual attention was directed to the vital signs monitor, particularly during crisis situations [23]. Few studies, however, have explored the distribution of visual attention that interdisciplinary medical teams use to gather the information for maintaining situation awareness in dynamic domains such as trauma resuscitation. We believe that knowledge obtained through this type of study will offer valuable insight into the design of information technology that supports complex and dynamic teamwork processes. In this work, we analyzed vital signs monitor use during resuscitation to understand how trauma teams might use other types of information displays in this setting.

Information Displays in Safety-Critical Teamwork

A common approach to supporting information sharing and situation awareness among medical teams is the use of status whiteboards and large wall displays. Information

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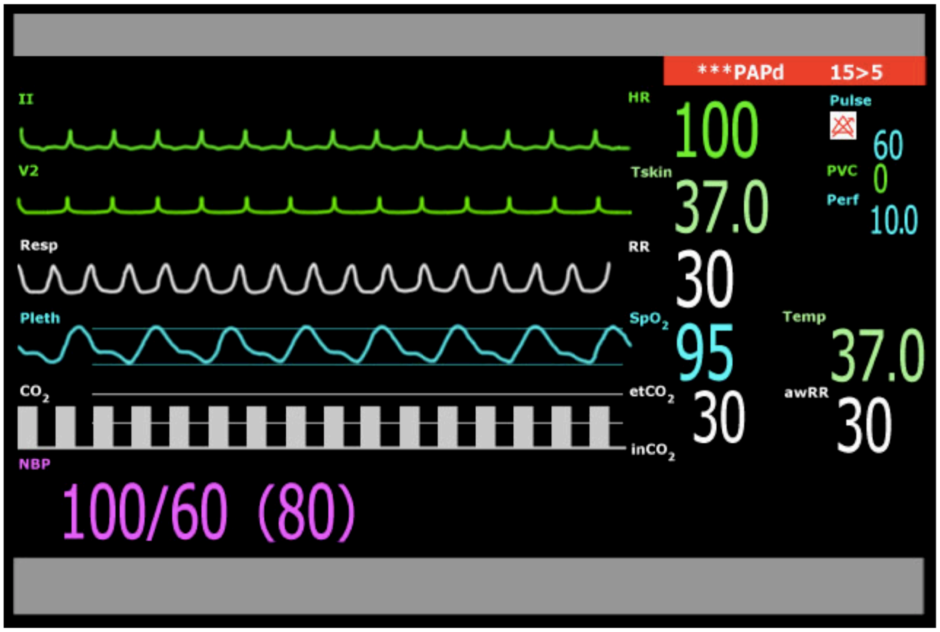

Waveforms		
II	EKG lead selection	C
V2	EKG lead placement site	C
Resp	Respiration	B
Pleth	Plethysmography (lung volume/capacity)	B
CO_2	Carbon Dioxide levels	A, B
Numerical Values		
HR	Heart Rate	C
Pulse	Pulse	C
Tskin	Skin Temperature	S
PVC	Premature Ventricular Contractions (arrhythmia)	C
Perf	Perfusion (blood flow)	C
NBP	Noninvasive Blood Pressure	C
RR	Respiratory Rate	B
SpO_2	O_2 Saturation Percentage	A, B
Temp	Temperature	S
$etCO_2$	End-Tidal (exhaled) CO_2	A, B
$inCO_2$	Inspired (inhaled) CO_2	A, B
awRR	Airway Respiratory Rate	A, B

Figure 1: Vital signs monitor displaying waveforms and numerical values of vital signs. The table on the right defines the displayed information. The last column indicates the ATLS protocol steps in which this information is used.

displays have been proposed for augmenting team situation awareness in a variety of medical settings, including emergency departments [25,26], operating rooms [3,5,20], critical care units [29], anesthesia [7], and even patient rooms. These displays and status boards have been shown to support both collocated and distributed work by facilitating task coordination, resource planning, communication, and problem solving. Effective integration and display of large amounts of data has also been used for improving awareness in other safety-critical settings, including traffic control rooms [13,14,15] and nuclear power plant control rooms [19]. As a safety-critical, socio-technical system, trauma resuscitation remains one of the few medical settings without information technologies that support teamwork. Introducing large displays that include vital signs data augmented with contextual information about patient status and team tasks could provide additional support for maintaining situation awareness.

BACKGROUND & CONCEPTUAL FRAMEWORK

Trauma Resuscitation Process Overview

Trauma resuscitation is a specialized medical domain in which critically injured patients are treated in a dedicated room in the emergency department (*trauma bay*). During resuscitation, an interdisciplinary team of medical specialists (*trauma team*) must identify and treat potentially life-threatening injuries, with the need for a critical decision about once a minute [8]. The resuscitation process is one of the most demanding in healthcare, requiring the team to focus on a common task for a short time period (on average, 20 minutes) while adapting to complex and changing circumstances driven by patient injury. Unlike other clinical settings, patient management during resuscitation relies mostly on emerging rather than existing information.

To improve efficiency, reduce errors, and guide the initial evaluation of patient injuries, the Advanced Trauma Life Support (ATLS) protocol has been developed and adopted by medical professionals worldwide [1]. The protocol includes the basics of early trauma care and focuses on identifying life-threatening conditions by adhering to the following sequence of steps ("ABCDE"): (1) **A**irway assessment and maintenance [A]; (2) **B**reathing assessment and ventilation [B]; (3) **C**irculation assessment [C]; (4) **D**isability or neurological status assessment [D]; and (5) **E**xposure and environmental control [E]. These initial assessment and management procedures are done sequentially, in the order of importance, with periodic reevaluation of each system to identify any deterioration in the patient status [1]. Steps following the initial evaluation include a head-to-toe evaluation for other injuries (Secondary survey [S]) and the initiation of definitive care [1]. Although patient evaluation is complex and sometimes requires deviation from the protocol, this structure provided a framework for analyzing the tasks performed by the team.

Vital Signs Monitor

Because adequate resuscitation is best assessed by improvement in physiological parameters (e.g., heart rate, blood pressure, pulse), the vital signs monitor is central to patient care and team performance. The monitor is currently the only electronic display in the trauma bay at most hospitals. The information displayed on vital signs monitors, however, is based solely on data read from sensors attached to the patient's body. This sensor-based data is displayed in the form of waveforms or numerical values (or both), and includes heart rate (HR), blood pressure, pulse, oxygen saturation levels (SpO_2), carbon dioxide levels (CO_2) inhaled and exhaled from the lungs, respiratory rate (Resp and RR), and temperature (Temp and

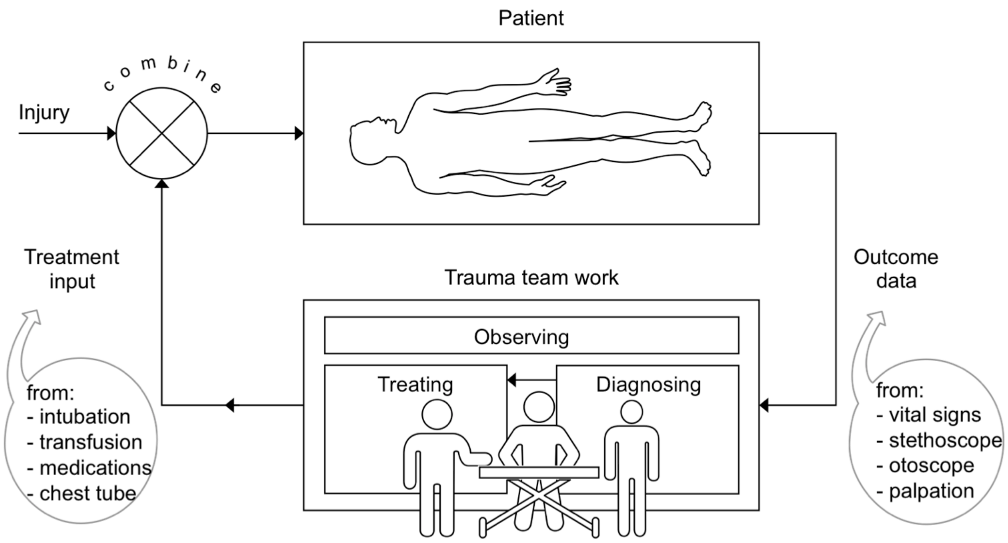

Figure 2: Feedback loop representation of the resuscitation process.

Tskin) (Figure 1). The waveforms represent the most recent trends of selected vital signs, but only span a short amount of time (less than a minute).

Trauma teams use the vital signs information to make critical decisions when treating severely injured patients. The vital signs display, however, mainly supports teams with information about the patient's airway [A], breathing [B] and circulation [C] (table in Figure 1). For example, information about oxygen saturation in the blood is used to determine if adequate levels of oxygen are being maintained or if an intervention for improving oxygenation (e.g., intubation) needs to be performed. To identify hypotension or hypertension (circulation issues), teams rely on heart rate, pulse, and blood pressure measurements. The vital signs monitor does not include information obtained through direct patient examination, such as airway obstructions [A], breath sounds [B], heart sounds [C], cognitive impairment [D], and types or extent of physical injuries [S]. It also lacks contextual information about team activities, treatments, and outcomes. Although the vital signs monitor provides a summary of the patient' condition, which in turn depends on the status of major physiological systems, the problems in each system are diagnosed and treated independently of each other.

Conceptual Framework: Feedback Loops in Trauma Resuscitation

Feedback loops are viewed as powerful mechanisms for augmenting human performance [28]. An example of a simple and successful feedback loop application is a speed limit sign coupled with a radar sensor attached to a large digital readout announcing "Your Speed," also known as driver feedback signs [11]. More recently, research in HCI and UbiComp has leveraged this concept by featuring technologies and applications that allow fast and easy collection of energy usage data and personal health data to trigger behavior change [9,10].

In the context of medical work, feedback allows clinicians to identify and correct poor decisions before they lead to undesirable outcomes [28]. Drews and colleagues studied how anesthesiologists used visual display feedback for maintaining the level of anesthesia administered during surgery [6,7]. They found that feedback helped anesthesiologists formulate drug-dosing strategies, particularly during critical moments. In contrast, our work views the entire trauma team involved in multiple feedback loops, with each feedback loop addressing a major physiological system (Airway, Breathing, Circulation, and Disability), as outlined by the ATLS evaluation protocol. We can view the resuscitation process as consisting of several independent feedback loops for two reasons. First, although connected, physiological systems are sufficiently independent from one another to allow clinicians to treat each system independently during resuscitation. For example, airway patency depends on whether there are obstructions in the patient's airway; breathing depends on the status of the chest; and circulation depends on the status of circulatory system. In fact, the ATLS protocol recommends that the evaluation of these systems be performed sequentially and independently of each other. During the primary survey, the team diagnoses and treats complications in each physiological system by collecting evidence about its status, determining and administering treatments, and interpreting patient responses to those treatments (Figure 2). Each feedback loop originates with an event (e.g., injury or treatment) and continues with the team's observations of the effects of this event (e.g., injury symptoms or response to treatment). Based on the feedback obtained, the team then decides whether to perform a treatment, pause and temporarily switch to another physiological system (different feedback loop), or conclude the current feedback loop (Figure 2). Second, all major interventions (e.g., intubation or chest tube insertion) are closely coordinated and supervised by a single person (team leader), making it difficult to perform two interventions simultaneously. In addition, each intervention is followed by a waiting period to evaluate the effects of the treatment (feedback). The timeliness of this feedback depends on how fast the team can perform treatments and how fast the patient reacts to those treatments. The team may start working on a different system while waiting for feedback, but often cannot perform major work on more than one physiological system at the same time.

Viewing the resuscitation process using a feedback loop perspective allowed us to situate monitoring activities within the context of work. This perspective yielded new insights into team dynamics and the role of vital signs monitor in supporting trauma teamwork. In short, understanding the dynamics of different feedback loops, as well as team activities associated with those feedback loops, will help inform what information to display, when in the process, and for how long.

RESEARCH GOALS, QUESTIONS & CONTRIBUTIONS

The goal of this paper is twofold. First, we examine when in the resuscitation process references to the vital signs monitor happen. Second, within this feedback loop-driven process of evaluation and treatment, we characterize the role that the vital signs monitor plays in supporting teamwork. We structure our observations by adopting the feedback loop concept to understand how teams use the vital signs monitor to reach diagnoses, decide on treatments, and monitor patient outcomes. We ask: Who are the most frequent users of the vital signs monitor? How often is the monitor used? When is the monitor used? How much time is allocated to the monitor?

The key contributions of this paper are:

• Characterization of the role of a visual display in time-critical medical teamwork.

• Identification of three types of information behaviors in time-critical medical teamwork relative to a visual display.

• Empirical quantification of the length of a safe amount of look-away time from the patient in emergency situations.

METHODS

Dataset: Simulated Resuscitations

We analyzed 12 high-fidelity simulated resuscitations from a pediatric Level 1 trauma center in the US mid-Atlantic region. There were 12 unique trauma teams in total, each composed of a team leader (senior surgical resident or emergency medicine physician), physician doer (junior surgical resident), anesthesiologist, primary nurse, scribe nurse, technician, respiratory therapist, and medication nurse. These team members were recruited from individuals usually serving in these roles.

The simulations were performed in an actual trauma bay with high-fidelity patient mannequins and the usual medical equipment and materials available. Team members positioned themselves around the patient according to their prescribed roles and positions: anesthesiologist and respiratory therapist stood at the head of the stretcher for easy airway access; scribe nurse and team leader stood at the foot of the bed for better overview of the patient and team; physician doer was positioned to the right and primary nurse to the left of the stretcher for performing interventions; technician was positioned to the right for easy access to the monitor and sensors; and medication nurse stood near the medication bench off to the left (Figure 3). The mechanism of injury and other pre-hospital information was relayed to the team when the patient mannequin was brought into the trauma bay. Real-time patient vital signs (e.g., heart rate, oxygen saturation, and respiratory rate) were displayed on the monitor after the technician connected the sensors to the mannequin. Vital signs and symptoms were manipulated electronically based on a preset script, and depended on the interventions performed by the trauma team. Information about the patient's conditions that could not be discerned from the mannequin (e.g., pulses or Glasgow Coma Scale (GCS) score to determine neurological disabilities) was verbally provided when prompted by team member actions.

We analyzed two scenarios performed by trauma teams. The first scenario (*Scenario A*) involved a 5-year-old female who was in a high-speed car accident. Teams needed to respond with interventions including intubation (a procedure in which a tube is inserted into the trachea to assist the patient's breathing) and fluid administration to stabilize blood pressure. The second scenario (*Scenario B*) involved a 3-year-old male who was hit by a car and dragged. Trauma teams were expected to perform chest decompression using a needle to release increased air pressure in the space between the lung and chest wall (tension pneumothorax), and fluid administration to stabilize blood pressure. The mannequins had features that allowed the teams to perform the resuscitation procedures required for each scenario (e.g., listen to breath sounds, insert tubes, and feel for injuries). The mannequins were also marked by artificial injuries for scenario realism.

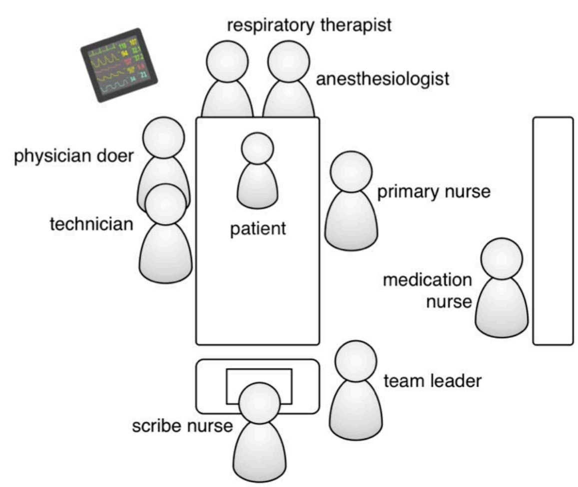

Figure 3: Team arrangement and monitor placement.

Two video cameras captured the simulations, providing different views of the trauma team and the trauma bay. One camera provided a rear, overhead view of the trauma room and the other provided a closer side view of the team and the vital signs monitor. The average length of the simulations was 9 minutes, ranging from 5 to 13 minutes.

Benefits and Limitations of Using Simulated Resuscitations

While the simulations were of high fidelity, it was not possible to replicate all aspects of the patient injuries and responses to interventions. There were, however, several benefits to implementing simulations versus observing live resuscitations. By performing simulations, we were able to videotape the resuscitations and perform detailed analyses not possible through direct observation. With simulations, the scenarios and patient conditions were presented to the teams in a consistent manner to control for variability in injuries, treatment, and outcomes, allowing us to focus on the larger themes of teamwork, workflow, and vital signs monitor use. The resuscitation scenarios we analyzed allowed us to explore several kinds of interventions. They did, however, limit the diversity of information that was exchanged and tasks that we observed.

Data Analysis

We used a three-step process for data analysis. We started with a detailed transcription of simulation videos and coding of team tasks and communication to enable subsequent analyses of tasks and monitor use behaviors within feedback loops. We then analyzed monitor looks, their distributions and frequency. Finally, we analyzed team tasks associated with different feedback loops to understand the context in which the monitor was being used.

Transcription and Coding of Simulated Resuscitations

One researcher transcribed the simulations into a spreadsheet by recording the tasks in the order that they were performed. The tasks included patient assessments, diagnoses, medication preparation, interventions, and references to information sources for both gathering data and obtaining feedback. We also transcribed team dialog, including the speaker, listener, and statement to understand the context of the tasks. A data dictionary was created to standardize the transcription and coding process; it included the tasks performed according to ATLS with a corresponding code (ABCDES). Two researchers coded the transcripts independently and applied multiple codes where necessary. Coding disagreements were minimal and were mainly concerned with tasks that were not initially categorized based on the protocol. All disagreements were resolved through discussion and codes in the transcripts were updated to reflect the decisions.

While the videos afforded rich and unobtrusive analysis, there were several difficulties encountered during the transcription process. Due to the fast-paced, noisy environment and diverse teams, it was sometimes difficult to hear what people were saying or to identify the speaker. The transcriber was able to slow speech and actions and record them in the greatest possible detail. Having two simultaneous videos from different angles also alleviated transcribing difficulties. To assess the representativeness of the transcripts, we performed checks with trauma experts and the individuals that facilitated the simulations.

Analysis of Vital Signs Monitor Looks

Using the transcripts and videos, another researcher recorded the instances in which team members looked at the vital signs monitor, including how many times each individual looked and the amount of time they spent looking at the monitor. We used the time-stamping function in Transana, an open source video transcription software, to record the start and end times of monitor looks by each team member. To manage multiple, overlapping looks at the monitor, the data was placed into a separate spreadsheet and sorted by start time and then by team member. Start times were then matched with end times, and lengths of looks were calculated, which also allowed us to check for accuracy and missing data points.

Using this data, we created histograms showing the frequency of durations of looks across all simulations (see Figure 7), as well as the look durations for each team member (see Figure 8). Based on the observed drop in the frequency of monitor looks over 3 seconds, we chose 3 seconds as a reasonable threshold to distinguish between short and long looks (see Figure 7). Monitor looks ≤3 seconds were considered *glances* and looks that were >3 seconds were considered *scrutiny* [24].

In addition, for each simulation, we graphed the distribution of monitor looks by showing (a) the total number of monitor looks per 30-second interval, and (b) the total duration of monitor looks per 30-second interval (see bottom two charts in Figure 4 and Figure 5). If a look extended into another 30-second interval, it was counted in the frequency of the first 30-second interval that it appeared in to facilitate our data analysis. We further differentiated the distributions of monitor looks for leaders and anesthesiologists because they viewed the monitor longer or more frequently than other team members.

Analysis of Feedback Loops

To situate monitor use behaviors in the context of work, we also visualized tasks that teams performed for each feedback loop (or ATLS component) on a timeline, for each simulation (e.g., top chart in Figure 4). To create these visualizations, we first used the transcripts to identify tasks within each feedback loop and then used videos to place the tasks on a timeline. Visualizations of feedback loops and graphed distributions of monitor looks were then aligned, resulting in a three-part visualization for each simulation (e.g., Figure 4). We used these charts to identify and explain monitor use behaviors in the context of the tasks.

RESULTS

We report our results in three parts. First, we describe the trauma team workflow from a feedback loop perspective to

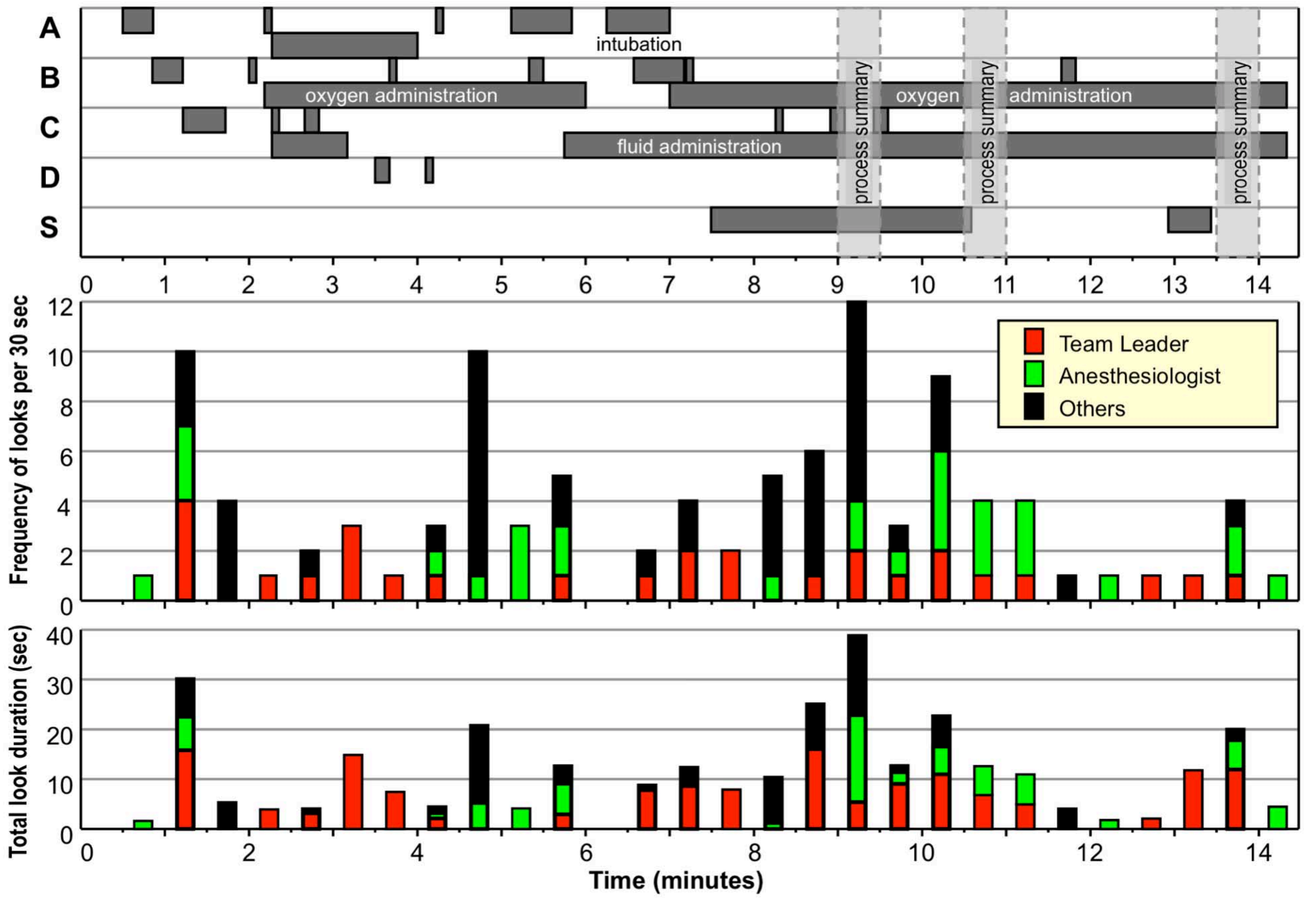

Figure 4: Top chart: Visualization of resuscitation tasks corresponding to feedback loops or ATLS steps for Scenario A, Team 1 (A stands for the Airway step or feedback loop, B for Breathing, C for Circulation, D for Disability, and S for Secondary survey). Bottom two charts: Distribution of frequency and total duration of monitor looks per 30-second interval.

help situate our analysis of monitor looks. We then characterize the use of the vital signs monitor within the context of trauma teamwork. Finally, we discuss team roles and how their work was distributed across feedback loops to gain further insight into team workflow and how best to support it with supplemental information displays.

Situating Vital Signs Monitor Use in Feedback Loops

Although we created three-part visualizations of tasks and monitor looks for all 12 teams, due to space constraints we show visualizations for only two teams, each from a different scenario (Figure 4 and Figure 5).

Our observations showed that teams initially followed the resuscitation protocol (from A through C), starting with a quick survey of the Airway [A] (by stabilizing the neck and assessing the airway patency), Breathing [B] (by listening for breath sounds and providing supplemental oxygen), and Circulation [C] (by palpating for pulses), as shown in top charts in Figure 4 and Figure 5. After completing these initial evaluation steps, the teams focused on the feedback loop involving the most critical intervention: intubation of the trachea [A] in Scenario A, and chest decompression or chest tube placement [B] in Scenario B. Critical tasks included monitoring oxygen saturation and blood pressure, as well as examining breath sounds and pulses.

We found that the frequency and duration of monitor looks varied over the course of resuscitation and depended on the tasks and team activities. The middle charts in Figure 4 and Figure 5 show the frequency of monitor looks over time for all team members. The bottom charts show the total duration of monitor looks. A possible explanation for this variability may be that the types of information sought during periods of frequent scrutiny differed from those sought during periods of frequent glances. Alternatively, it may be that teams limited the duration of their looks because they needed to focus on the patient. We next discuss these observations in greater detail.

Iterations of Feedback Loops

Teams continuously monitored the status of different physiological systems through corresponding feedback loops. Most of the time, teams were able to address the problems they diagnosed within a single iteration of a loop. For example, Team 1 in Scenario A decided that the patient needed additional oxygen and intubation based on decreased oxygen saturation and the lack of patient responsiveness at 2′15″ (Figure 4, top). They successfully

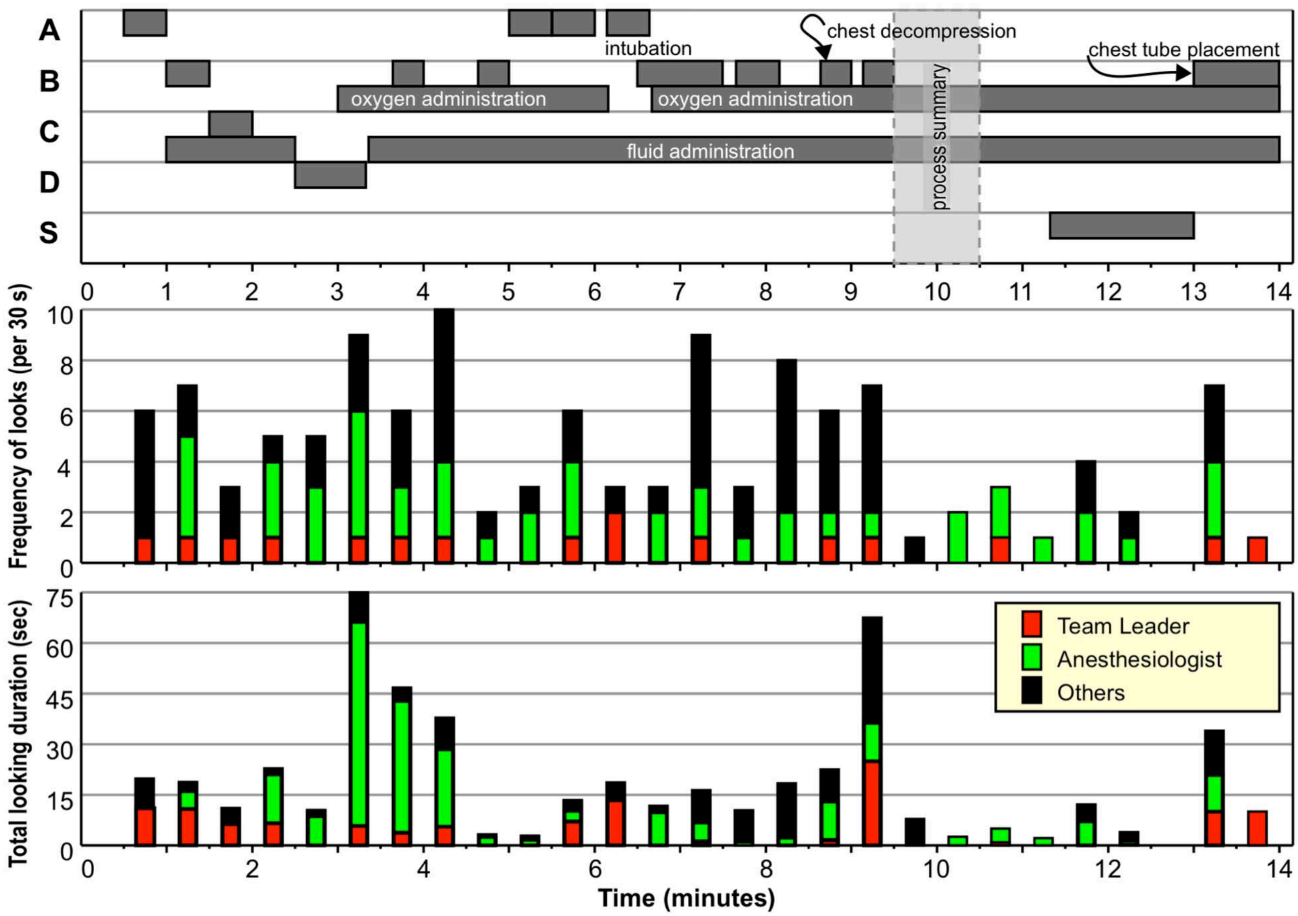

Figure 5: Top chart: Visualization of resuscitation tasks corresponding to feedback loops or ATLS steps for Scenario B, Team 5 (A stands for the Airway step or feedback loop, B for Breathing, C for Circulation, D for Disability, and S for Secondary survey). Bottom two charts: Distribution of frequency and total duration of monitor looks per 30-second interval.

completed intubation at minute 7 and then continued monitoring the airway status through brief assessments and summaries of vital signs ("process summary" in Figure 4).

Teams sometimes reiterated one or two feedback loops several times until multiple interventions finally led to patient improvement. For example, Team 5 in Scenario B iterated the Breathing feedback loop three times before successfully addressing the tension pneumothorax (Figure 5, top). At minute 1, they first diagnosed diminished breath sounds [B] and ordered oxygen administration, which started at minute 3. They then assessed breath sounds several times to observe the effects of oxygen administration (at times 3′40″ and 4′40″). After seeing no improvement, the team decided to intubate the patient, believing that this intervention would help (note their switch to the Airway loop). Breath sounds, however, remained diminished, leading the team to finally diagnose the patient with a tension pneumothorax and perform chest decompression at 8′40″. Even this second iteration did not fully address the underlying problem, triggering the third iteration and chest tube placement at minute 13.

Summaries of vital signs and patient status served as a mechanism for maintaining team situation awareness and ensuring that all critical tasks were completed. Team leaders often provided a process summary (and in some cases multiple summaries) at the beginning, middle, or end of the resuscitation. As an example, the team leader on Team 5, Scenario B summarized the process at 9′30″, including the mechanism of injury, interventions, and tasks in progress (Figure 5, top):

"*While he's putting the tube in, let's summarize. 2 year old, MVC [motor vehicle crash] hit and drag. Came in with an airway. We intubated secondary to hypoxia, needle decompressed, followed along with chest tube and fluids. Otherwise, external marks include tire tracks on the left chest and abrasions on left lower extremity as well as the left head. Anything else?*"

Switching between Feedback Loops

Trauma teams often switched between tasks from different feedback loops. For example, all teams in Scenario A began by assessing the Airway and ordering intubation, but temporarily switched tasks to the Circulation loop and prepared intravenous (IV) access for administering intubation medications. Another example occurred in Scenario B, when Team 5 switched from assessing breath sounds in the Breathing loop to intubating the patient in the

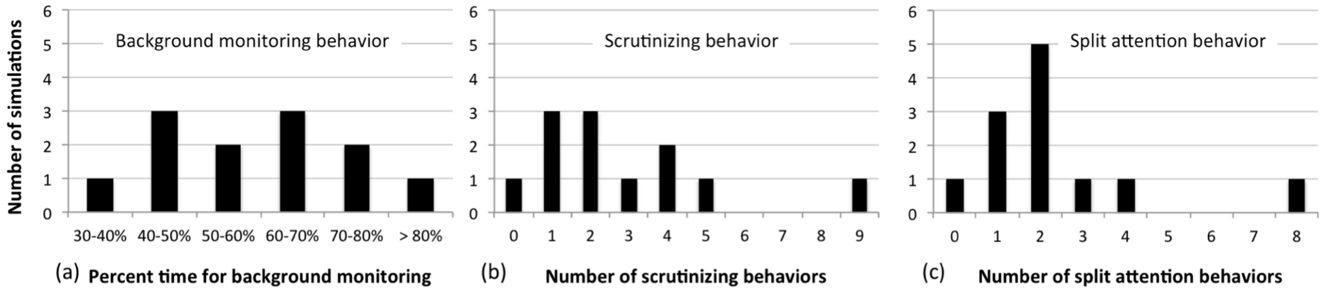

Figure 6: Vital signs monitor use behaviors across all 12 simulations. (a) Distribution of background monitoring behavior. (b) Distribution of scrutinizing behavior. (c) Distribution of split attention behavior.

Airway loop, and then back to Breathing where they decompressed the chest, as described above.

Some tasks had sequential order requirements as well. Intravenous access [C] needed to be established to administer fluids [C] or medications necessary for intubation [A]. It was also important to assess for brain injury before medicating the patient by examining the pupils and assigning a GCS score, an indicator of the patient's neurological status [D].

Switching between feedback loops seemed to occur for three reasons: (1) the requirement to attend to overlapping tasks from different feedback loops; (2) the need to suspend major tasks in the current loop while preparatory work for that loop was being completed; and (3) the sequential task dependencies across different loops, when one feedback loop could not proceed without completing tasks from another feedback loop.

Monitor Use Behaviors & Intensity of Looks over Time

Overall, the frequency and duration of monitor looks were relatively low during resuscitations, representing *background monitoring* of the patient's vital signs while focusing on patient care. These quick looks correspond to low bars in both frequency and duration—the bars with up to five looks in frequency and up to 10 seconds in total duration (see bottom two charts in Figure 4 and Figure 5). We chose 10 seconds for total duration as a reasonable threshold because each of the five looks is then about 2 seconds long, representing a glance. The background monitoring behavior was prevalent across all resuscitations, accounting for more than 50% of monitor looks in 8 out of 12 events (Figure 6(a)).

We also observed peaks (high bars) in both the frequency and duration of looks, representing *scrutinizing behavior*. These peaks occurred while teams were diagnosing patient conditions, followed by major interventions ("diagnosing" in Figure 2), and during "process summaries." For example, Team 1 in Scenario A had two high frequency peaks in the intervals 1′–1′30″ and 4′30″–5′ (Figure 4). The first peak occurred during initial evaluation of the airway, breathing, and circulation when the team diagnosed the need for oxygen administration [B] and intubation [A]. The second peak occurred while the team was waiting for the start of IV fluid administration, which then enabled them to start treating the airway by administering intubation medications. The remaining peaks coincide with process summaries, during which teams continued monitoring and diagnosing. We observed that all team members looked at the monitor during summarization, especially when the leader noted any changes in vital signs, as shown in this example: "*Open to suggestions guys. We're well ventilated and well oxygenated. Our heart rate has come down dramatically. Our blood pressure is up with the IV fluid.*"

Similarly, during the 1′–5′ interval, Team 5 in Scenario B had several high peaks in frequency and duration corresponding to the observation and diagnosing phases within the Breathing feedback loop (Figure 5). Another peak occurred during the interval 7′–8′30″, when they diagnosed the patient with a tension pneumothorax after assessing the patient's breath sounds. Peaks were also observed after chest decompression from 9′–9′30 and as the team performed chest tube placement between 13′–13′30″. During these interventions, the team needed to monitor the patient's oxygen saturation and carbon dioxide levels after intubation. They also needed to ensure that the chest tube was placed properly and the patient's breath sounds were improving. On average, we found 2.8 scrutinizing behaviors per resuscitation (Figure 6(b)). This low number of scrutinizing behaviors overall can be explained by the fact that most teams succeeded in diagnosing the complications in one to two loop iterations. The outlier team with nine scrutinizing behaviors (Team 4 in Scenario B) had a less experienced physician doer, but a proactive team leader who made diagnoses quickly and called out interventions promptly. Most of the monitor looks in this event came from the anesthesiologist, who monitored the vital signs for everyone and reported them aloud. The team leader noticed this behavior and used the anesthesiologist as a proxy so he could focus on the patient.

Finally, we observed that some high peaks in frequency did not have corresponding peaks in duration. We defined this behavior as *split attention*, which occurred during complex procedures when the team needed to maintain attention on the patient while also monitoring the displayed vital signs.

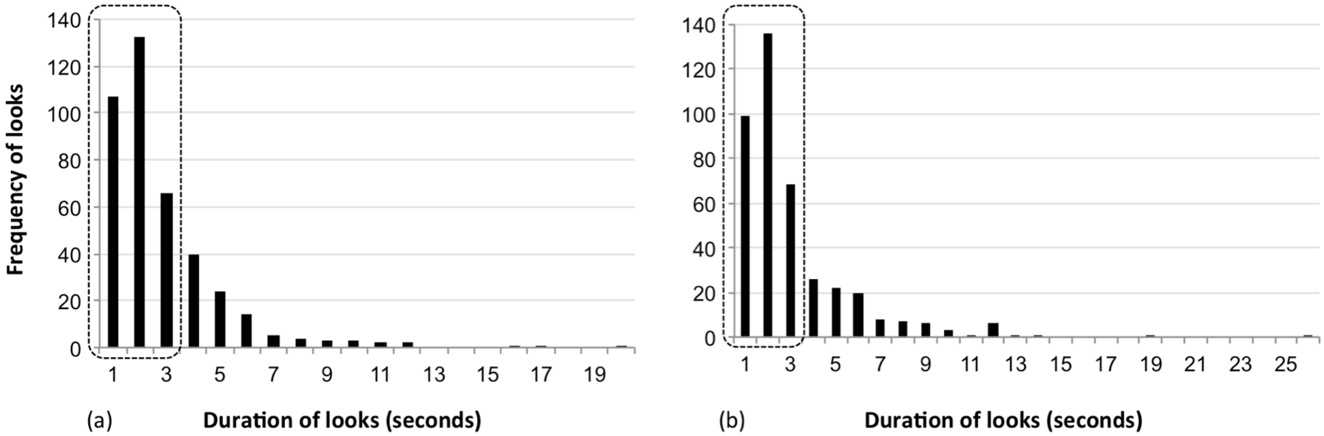

Figure 7: Durations of the vital signs monitor looks across 6 simulations for Scenario A (a) and 6 simulations for Scenario B (b).

For example, peaks in frequency during intervals 4′–4′30″, 5′30″–6′, and 7′–9′ for Team 5 in Scenario B (Figure 5, middle) do not have corresponding peaks in duration (Figure 5, bottom). During the first interval (4′–4′30″), the team was addressing a Breathing problem by frequently looking at both the patient's chest and the vital signs monitor. Similarly, during the 5′30″–6′ interval, the team was addressing the patient's deteriorating airway. The team was preparing for intubation and had to maintain attention on both the patient and the monitor. Shortly after intubation, the scribe nurse pointed out that the oxygen saturation was falling to dangerously low values. As a result, the team continued splitting attention between the patient and the monitor during the 7′–9′ interval, especially as they performed chest decompression. On average, we found 2.3 split attention behaviors per resuscitation (Figure 6(c)). This low number of split attention behaviors overall can be explained by the fact that the patients required only a few complex procedures. Team 5 in Scenario B was an outlier, exhibiting a total of eight split attention behaviors. As described above, it took this team several loop iterations before diagnosing the problem, which required more time for both patient and vitals monitoring. The leader was also less proactive, mainly asking for information, reminding the team of protocol steps, and summarizing the process.

Although all team members looked at the monitor, the team leader and the anesthesiologist had more frequent and longer looks than others. This finding is not surprising given their roles—the team leader is supervising the process and anesthesiologist is responsible for airway management, which involved one of the critical conditions that needed to be addressed. As seen in Figure 4 and Figure 5, the leader had a relatively low frequency of looks, but was dominant in terms of the duration of looks.

Monitor Looks	Scen. A	Scen. B	Total
Glances (≤3 s)	305 (75%)	303 (75%)	608 (75%)
Scrutiny (>3 s)	100 (25%)	103 (25%)	203 (25%)
Total	**405**	**406**	**811**

Table 1: Distribution of glances and scrutiny across teams and scenarios, relative to the 3-second threshold.

Distribution of Looks across Teams and Scenarios

Our analysis of vital signs monitor looks in the context of feedback loops showed that trauma teams used the monitor to identify conditions that could not be found through physical examination of the patient. The monitor was an integral part of the resuscitation process and provided an information source that team members used to establish common ground and maintain situation awareness. We further examined how teams used the vital signs monitor with a particular focus on (a) how much time was allocated to the monitor and how often team members looked, and (b) the frequent users of the monitor.

Time Allocation and Frequency of Monitor Looks

Our data showed that most monitor looks were quick glances—3 seconds or shorter (75%) (Figure 7). This large percentage of glances is directly related to the prevalence of background monitoring behavior. The data also revealed many looks that were between a little over 3 seconds and 26 seconds (25%) (Table 1). Scrutiny was not as prevalent as glances, but we can infer that teams do have opportunities to look away from the patient and view the monitor in relative detail. The monitor look ratio of glances to scrutiny is approximately 3:1. Although we examined 12 unique teams in two scenarios (6 teams per scenario), it appears that the total numbers of glances and scrutiny were highly consistent between Scenarios A and B.

Five outlying monitor looks were longer than 15 seconds, all of which were made by team leaders or anesthesiologists (Figure 7). These unusually long looks at the monitor appeared to help team leaders and anesthesiologists track the changes in the patient's vital signs to determine the overall outcome of the treatments. These looks occurred during diagnosis or following major treatments. For example, after intubation, the team leader on Team 5 in Scenario A looked at the monitor and reported, "*Okay. She's improving with the [fluid] boluses. […] We've secured our airway.*" Similarly, the anesthesiologist and team leader on Team 1 in Scenario A both looked at the

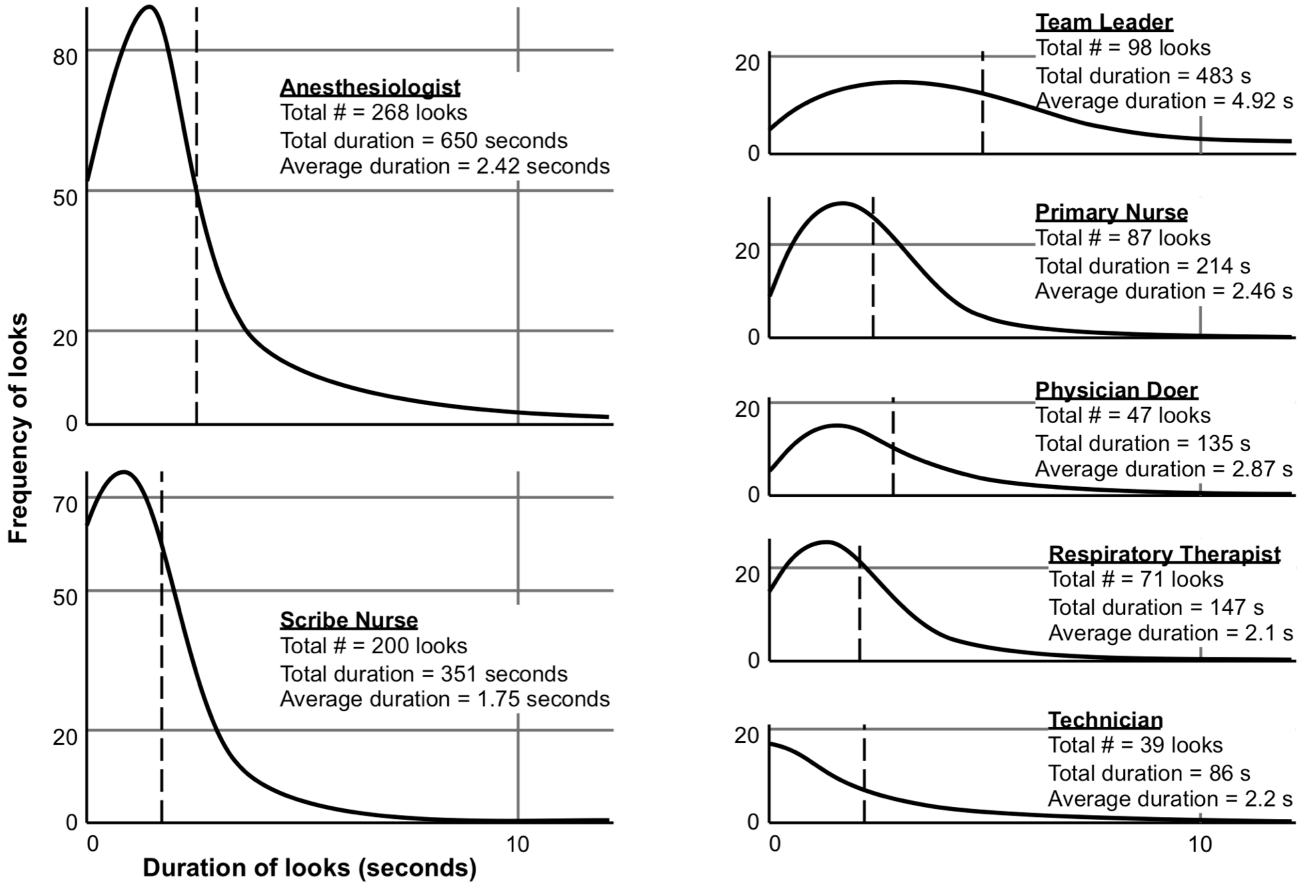

Figure 8: Curve-fitted approximation of the frequency of durations of the vital signs monitor looks for individual team members across all 12 simulations. Dashed lines mark the averages of durations.

monitor after the patient was intubated. The team leader reported, "*End-tidal [CO_2 exhalation level] is 33 guys, so from a respiratory point of view we're looking alright. Heart rate still coming down. Blood pressure is going up just a little bit so that's good.*" The longest look (25.4 s) came from the leader on Team 5 in Scenario B. Scenario B was more complex than Scenario A, and team members had difficulty diagnosing problems with the patient's breathing.

Monitor Attention across Team Members

We were also interested in understanding the different ways team members and teams as a whole used the monitor throughout the resuscitation process to identify design requirements for future displays. As our data showed, monitor use varied by team member role (Figure 8). Team leaders and anesthesiologists on all teams appeared to depend on the vital signs monitor the most, but exhibited distinctly different patterns of use. Team leaders were not among those who looked most often, but spent significantly longer amounts of time looking at the monitor than others (Figure 8). Based on our data, we concluded that most leaders relied on the monitor to maintain a high-level awareness of the patient's status and outcomes of the interventions performed. They appeared to analyze the monitor more deeply to determine the patient's conditions and the appropriate interventions. Team leaders also used the monitor to analyze trends in vital signs, which is demonstrated by the frequency of their scrutiny (Figure 8).

Anesthesiologists looked significantly more often, but on average spent about the same amount of time as everyone else except the team leader (Figure 8). Anesthesiologists used the monitor to ensure that the patient's vital signs were within a safe range, and to detect any adverse reactions to medications or interventions, especially those involving the airway and breathing. For example, the anesthesiologist in Team 4 of Scenario B looked at the monitor often and reported the feedback gathered back to the team.

Physician doers and technicians looked at the monitor less frequently than the rest of the team (Figure 8). They looked at the monitor mostly when silencing monitor alerts or when everyone else was looking. Physician doers typically focused their attention on the patient rather than on the monitor. They spent most of their time examining the patient, relying on other team members to report vital signs.

Technicians checked the monitor when connecting sensors to the patient. Their time was largely spent preparing IV access and retrieving materials for the team. Moreover, the team and room configuration positioned the physician doer and technician facing away from the monitor (Figure 3). They had to turn around to view the monitor and did so mostly when their eyes and hands were not busy.

Primary nurses, similar to physician doers and technicians, were busy with patient care—removing the patient's clothing, administering fluids and medications, and retrieving materials for the team. Respiratory therapists sometimes checked the oxygen saturation on the monitor when administering additional oxygen to the patient, but usually looked when other team members were also looking. Scribe nurses looked at the monitor frequently, but only for a few seconds at a time to gather information for documentation.

In short, decision making roles (team leader) looked significantly longer than others. They analyzed the display data for diagnostic purposes. Team members directly involved in patient care looked least frequently and for the shortest times. It also appeared that a fraction of monitor looks were the result of other people looking at the monitor or reporting information currently displayed, representing more of a confirmatory behavior for updating awareness of the changes in vital signs.

Roles and Work Distribution across Feedback Loops

Understanding roles and work distribution across feedback loops will help us further determine how to support the work of trauma teams with supplemental information displays. We need to know who is responsible for which tasks, what kinds of information they need for task completion, and how their work overlaps with the work of others. Established principles and guidelines for optimal trauma care published in [2] imply that there is a general division of labor defining specific tasks that each team member performs based on their role. We observed, however, that certain team members assumed the roles of others despite being "in charge" of particular tasks. This role switching behavior depended on differences in level of experience, position around the patient, or availability to perform a task. For example, the physician doer was normally responsible for examining the patient across different feedback loops, such as assessing the airway [A], listening for breath sounds [B], palpating for pulses [C], and assessing the patient's pupils [D]. Our observations showed that anesthesiologists often took over these tasks due to their convenient positioning at the head of the bed. Anesthesiologists also helped independently confirm the physician doers' findings.

Our research site is a teaching hospital where care providers frequently engage in on-the-job learning, and where teams are dynamically composed of team members with varying levels of experience and expertise. Several physician doers did not have experience with performing chest decompressions or chest tube placement, and followed directions from leaders and anesthesiologists. One anesthesiologist performed chest decompressions because the physician doer was uncomfortable with performing the procedure. Although the anesthesiologist's role is mainly to manage the patient's airway and oxygen administration, they are also skilled in performing other respiratory-related procedures. As confirmed by medical experts on our research team, these types of unpredictable circumstances also arise during actual resuscitations.

Primary nurses and technicians also frequently covered each other's tasks, filling in where the other left off on multi-stage tasks. For example, to complete the Circulation loop, technicians would place an IV access and primary nurses would prepare the fluids, connect the IV line to the infuser, and then hand the line to the technician to connect it to the access.

These observations imply that team members are distributed across multiple feedback loops. Team leaders acted as overseers of the process, and thus multiple feedback loops. They accounted for completed and incomplete tasks, pushed for information to conclude feedback loops, and determined what feedback loops needed to be reiterated. Managing multiple feedback loops required the leaders to maintain a high-level awareness of all the tasks completed, in progress, and pending. Because team members switch roles and engage in multiple feedback loops, it is important that they maintain awareness of information important to all roles, especially when temporarily assuming a different role.

DISCUSSION

During trauma resuscitation, teams collect evidence, diagnose, treat, and interpret patient responses, creating separate feedback loops for each component of the ATLS protocol. Our findings offer insights into how this feedback loop-driven process of trauma teamwork can be improved. Physical examination, verbal communication, and use of the vital signs monitor all serve as channels for receiving feedback to maintain situation awareness and support workflow. The vital signs monitor provides an overall summary of the patient's condition based on up-to-date sensor data (Figure 1), but does not provide the rich, contextual information needed to support situation awareness during the resuscitation process. We believe that trauma teams may benefit from additional displays to supplement the vital signs monitor with contextual information, provided that displayed information can be absorbed within a safe amount of look-away time from the patient. We have examined the frequency and duration of the vital signs monitor looks, and demonstrated how these variables are influenced by role and the stage of the resuscitation. Our study offers empirical evidence about the length of this look-away period, showing that medical teams have the time and cognitive resources to look at monitors in emergency situations.

Supporting Monitor Use Behaviors

We identified three distinct types of information behaviors relative to the vital signs monitor: (i) periods with a low frequency of glances, to maintain overall awareness of the process and patient status; (ii) peaks with a high frequency of glances, to split attention between the patient and the monitor; and (iii) periods with a medium frequency of scrutiny, to monitor trends in patient status over time.

Periods with a low frequency of glances (background monitoring behavior): Intervals with low numbers of glances occurred often and were distributed over the entire resuscitation (low bars in both frequency and duration charts in Figure 4 and Figure 5). During these intervals, the team was focused on their work and monitor viewing was a background activity for maintaining overall awareness. To support this monitor use behavior, the display should be peripheral, simple, and contain only essential information. Current vital signs monitors, which are mainly meant to provide a quick reference to current patient status, appear to meet the information needs during background monitoring.

Peaks with a high frequency of glances (split attention behavior): Intervals with high numbers of glances (high bars in frequency and low bars in duration charts in Figure 4 and Figure 5) occurred during critical moments in the resuscitation (diagnosis and intervention), when the team had to maintain attention on the patient while also checking for important information on the monitor. To support this monitor use behavior, displays should be peripheral and simple, but highlight information specific to the task at hand. Ideally, displays should be placed as near to the patient as possible to minimize the time spent switching between looking at the patient and the monitor. Also, display distance should be chosen in a way that does not require frequent changes in eye accommodation. A key issue, however, is that a computer system needs to distinguish split attention behavior from background monitoring for it to adjust the displayed information. Once the correct behavior is detected, task-specific information can be highlighted to make it easier to absorb within a short amount of time.

Periods with a medium frequency of scrutiny (scrutinizing behavior): Intervals with medium numbers of scrutiny (high bars in both frequency and duration charts in Figure 4 and Figure 5) occurred during diagnostic stages, when teams were collecting information and making diagnoses, and after major treatments. Because the monitor looks were relatively long (on the order of tens of seconds), the display could cease to be peripheral and provide richer information, and perhaps even include simple interaction. Designing displays to support this information behavior poses several challenges. First, there is still an issue of detecting scrutinizing behavior and distinguishing it from other monitor use behaviors. Second, once the scrutinizing behavior is detected, the question is whether the rich, contextual information should replace the basic vital signs monitor information, or whether to show this detailed information on a separate display. Replacing the vital signs monitor with a more detailed display may not be practical. Vital signs are critical to patient care and must always be presented to the team. Third, even if detailed information is shown separately, one may ask why it is not shown at all times, rather than only when scrutinizing behavior is detected. Although answering this question requires further investigation, we believe that having detailed information presented at all times may be unnecessary and distracting. Finally, the challenge is also in identifying what information to display given the large amount of information types relevant to the resuscitation process.

Providing Rich Contextual Information

Our data showed that a significant amount of time was spent on viewing the vital signs monitor. In particular, the leaders (decision making roles) appeared to scrutinize the displayed information for relatively long time periods and may benefit from richer contextual information, including (1) mechanism of injury; (2) highlights of changes in vital signs; (3) diagnoses, interventions, and outcomes; and (4) process-oriented information about the status of tasks for each feedback loop. This additional information may help the leaders manage the activities of multiple feedback loops from a high-level perspective by keeping track of the observations, treatments, and outcomes that occurred in each feedback loop during the resuscitation. Their summarizing behaviors also suggest that a display providing a reminder of the "story" with contextualized details of the resuscitation may be beneficial. These reminders would support team leaders when they review critical information to ensure that all injuries were assessed properly and to help prevent or remedy inconsistencies in team situation awareness. The challenge here is enabling seamless switching from basic to more complex information, or from peripheral to focal modes of viewing.

Time and space constraints, as well as proximity to monitors [18], prevent most team members from engaging in direct interaction with information displays in the trauma bay. Previous research has looked at using the nurse scribe as a proxy for capturing and displaying information for trauma teams in real time [22]. This solution would allow the nurse scribe to function as a human filter for the information relevant to teamwork without the need for team members to interact with an interface. Some interaction, however, such as panning and zooming in on vital signs with highlighted changes and events, would allow hands-off roles to conduct deeper analyses of the resuscitation process. Natural interaction modalities such as gestures could be used here as a way of addressing sterility and proximity issues [18].

Supporting Role Distribution across Feedback Loops

Despite being in charge of certain tasks, team members needed to be flexible to manage changing circumstances. Team members often performed tasks across different feedback loops, coordinated and shared work, covered other team members' tasks, and learned and taught new procedures. The nature of dynamic and tightly coordinated teamwork may necessitate a general information display for non-leadership roles to avoid tunnel vision for any particular role. Such a display could provide the status of tasks in each feedback loop to promote a shared awareness among the team. There may also be opportunities to assist trauma team members in training with quick visual guides for recalling how to do procedures such as locating chest tube insertion points. Multiple monitors displaying the same information in different positions around the stretcher would allow roles such as the physician doer and technician to view patient information more easily and may also reduce the reliance on others to call out information.

Finally, monitor usage data can be used for explaining or even predicting tasks and behaviors in the stressful trauma bay environment. For example, increased split attention behavior may be correlated with increased stress levels and workload because clinicians may be having difficulty making diagnoses or needing to make a lot of interventions to resuscitate the patient. Displaying this type of information through ubiquitous, context-aware technologies may help clinicians outside the trauma room discern the severity or difficulty of the case, and whether to offer assistance. Further research is required to determine why teams engage in different monitor use behaviors.

FUTURE WORK

In future work, we plan to implement other techniques to enhance the data collected about monitor usage. Mounting additional cameras on the monitors themselves may help us better identify when and how long team members are looking at the monitor. Although eye-tracking technology is commonly used in studies of visual scanning and monitoring [12,17,21,23], we found this technology inadequate for the trauma bay environment for several reasons. First, current eye-tracking technology does not support gaze tracking of multiple people at a time. Second, the distances at which eye-tracking can currently be used is less than 10 feet, which is insufficeint for the trauma bay coverage. We also plan to conduct interviews with team members to learn more about their monitor use and, in the case of team leaders, how they analyze trends in vital signs. Additional analyses of simulated resuscitations performed under different injury scenarios will allow us to better identify patterns in team workflow and use of the vital signs monitor. Finally, we hope to extend our work into the field where we can analyze actual trauma resuscitations.

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