Understanding Delay Awareness and Mitigation Mechanisms through an Iterative Design and Evaluation of a Prototype Alert System for Complex Teamwork

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Almost half of the preventable deaths in emergency care can be associated with a medical delay. Understanding how clinicians experience delays can lead to improved alert designs to increase delay awareness and mitigation. In this paper, we present the findings from an iterative user-centered design process involving 48 clinicians to develop a prototype alert system for supporting delay awareness in complex medical teamwork such as trauma resuscitation. We used semi-structured interviews and card-sorting workshops to identify the most common delays and elicit design requirements for the prototype alert system. We then conducted a survey to refine the alert designs, followed by near-live, video-guided simulations to investigate clinicians' reactions to the alerts. We contribute to CSCW by designing a prototype alert system to support delay awareness in time-critical, complex teamwork and identifying four mechanisms through which teams mitigate delays.

CCS Concepts: • **Human-centered computing** → Collaborative and social computing theory, concepts, and paradigms → Computer-supported cooperative work

Additional Key Words and Phrases: Alerts, alert fatigue, clinical decision support, complex teamwork, delay awareness, delay mitigation, trauma resuscitation

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1 INTRODUCTION

Trauma is one of the leading causes of death for individuals under 45 in the United States [60]. About 50% of deaths classified as "preventable" are associated with a delay or error during trauma resuscitation, the initial evaluation and management of critically injured patients [37].

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Among severely injured adults with hypotension, the risk of death increases by 1% with every three minutes of delayed care [37]. Improved situational and temporal awareness during trauma resuscitation can improve patient outcomes by reducing medical errors and treatment delays [1][20].

Maintaining situational and temporal awareness during trauma resuscitation is challenging due to the complexity of the patient's injuries and the multidisciplinary nature of the work. A recent study showed that teams responding to patients with traumatic injuries underestimate time by as much as 28% [47], delaying the next phase of care. Clinicians also misclassified non-critical patients as critical despite incoming patient data showing their accurate status [49], highlighting the importance of situational awareness in preventing delays. Information displays [59] and cognitive aids [35] have been evaluated in several medical settings to improve temporal and situational awareness. One low-tech intervention used non-traditional simulation to improve the team's closed-loop communication by blindfolding the team leader to tasks performed by the team [45]. Although these approaches helped improve user-reported situational awareness, few studies have addressed delay awareness through computerized support. Understanding delay awareness and response to delays in complex teamwork is necessary to inform the design of effective computerized support.

This paper presents the findings from an iterative user-centered design process to develop a prototype alert system for supporting delay awareness in complex medical teamwork. Our goal in this paper was two-fold. First, we examined how trauma team members experience and manage delays during dynamic and safety-critical patient care. Although we have some understanding of delays and their effects on workflow in surgical settings [41][44][52], little is known about clinicians' experiences and management of delays in dynamic medical teamwork. We sought to answer three research questions under this first subgoal: (1) What are the most common delays in emergency medical care? (2) How do clinicians experience these delays and become aware of them? (3) What are potential visual mechanisms for communicating delays to clinicians? Second, we designed a prototype system that supports team awareness of delays through visual alerts. We then used this prototype to understand the team's response to delays. Here, we sought to answer our last two research questions: (4) How do clinicians perceive visual representations of delays? (5) How do clinicians react to and mitigate delays? To achieve our research goal and answer these questions, we conducted a series of research activities, including interviews, card-sorting workshops, a design survey, and near-live, video-guided simulations. Through this design and evaluation process, we identified (a) most common delays in emergency medical care, (b) alert design preferences for two major role types within the resuscitation team (activity leaders and activity performers), and (c) common team-based strategies for mitigating delays.

We make two contributions to computer-supported cooperative work (CSCW) research: (1) a proof-of-concept for a prototype alert system that triggers awareness of delays in complex teamwork and (2) a delay mitigation framework with four mechanisms through which teams mitigate delays: request information, report progress, request or perform an action, and request or perform a modification. Understanding how teams in dynamic and complex work environments mitigate delays facilitates the design and development of computerized support for delay mitigation.

2 RELATED WORK

2.1 Awareness in CSCW and Human Factors Literature

Designing a system to improve delay awareness requires a clear understanding of how teams experience delays and how they act when they become aware of delays. Within CSCW, researchers have typically examined awareness needs in workplace settings [38][56][78]. For example, office-based workers were observed using shared public information such as displays, employee manuals, and the actions of co-workers to make sense of their activities [57]. Although clinicians in emergency medical scenarios such as trauma resuscitation also use similar artifacts to support awareness [52], the nature of short-term, *ad hoc* events differs from long-term work performed in an office. Trauma teams are "loosely formed" [76], with team composition fluctuating both during and between resuscitations. Team members do not consistently work with each other and can be new to the institution. As a result, team members can lack adequate social and situational awareness during resuscitations. Team members can also enter and leave the room at various times. People arriving late interrupt ongoing work, often asking questions for already reported information, which leads to poor communication [76].

CSCW research on awareness in emergency medical settings has identified four critical facets of awareness at the team level [51]: temporal and elapsed time awareness, team member awareness, task awareness, and process awareness. Awareness of elapsed time is critical for coordinating work and scheduling. Kusunoki et al. [51] described elapsed time awareness as knowing the estimated time of the patient's arrival, the time since the patient arrived, the time since certain tasks, and the time since changes in patient status. Team member awareness allows workers to effectively collaborate based on their knowledge of the location of other team members, their work status, and availability [8]. Social awareness in *ad hoc* contexts focuses on understanding who else is present and the status of other team member activities [52]. Task and process awareness were initially defined in research on articulation work as workers displaying their actions and monitoring the actions of others to determine the status of tasks [14][75]. Process awareness is also described as knowing the sequence of primary tasks, tasks due next, and the status of the process [14]. Because workers need to know the status of past, present, and future activities [52][46][71], task and process awareness enable workers to coordinate and manage future work.

To our knowledge, delay awareness—a combination of temporal, situational, task, and process awareness—has received little attention in CSCW research. Few studies have investigated how complex teams experience and mitigate delays during time-sensitive tasks. Burian et al. [12] studied anesthetists' responses to critical events like delays and errors, identifying four major factors that affected their response: the event type, the team members, the individual that is responding, and the environment and its resources. This analysis, however, focused on delay response by a single medical specialty conducting an individual task rather than delay response by an interdisciplinary team of different role types. Dismukes et al. [26] analyzed flight crews during challenging and stressful situations to identify the behaviors that lead to errors and delays, including inadequate communication, improvised task execution, poor decision making, and prioritization errors. Although this study highlighted critical behaviors leading to delays, it did not investigate how teams responded to or mitigated these delays. Webman et al. [81] found that teams respond to non-routine events during trauma resuscitation by "compensating" and "acknowledging" these events. In this paper, we extend this prior work by identifying and unpacking the mechanisms used by teams in dynamic work to mitigate delays once they become aware of them.

Human factors research has also studied the concept of awareness, defining it as the ability to perceive, understand, and predict elements in specific environmental, temporal, and spatial contexts [31]. This awareness approach has been adopted in domains like air traffic control [65], healthcare [4][34], and recently in autonomous driving [33]. Healthcare practitioners have increasingly used frameworks from human factors research to improve teamwork efficiency and awareness, including frameworks focused on patient safety (e.g., SEIPS [43][83]), and personnel training and protocols [10][11][82]. For example, West et al. [82] showed that applying crew resource management (CRM) techniques during patient data collection at the beginning of each shift improved communication and reduced delays in nursing units. Because our research focuses on introducing computerized support at the team level rather than the work system level, we found that the CSCW approaches to awareness support were more appropriate for our work.

2.2 CSCW Research on Supporting Awareness in the Medical Domain

User-centered design (UCD) approaches have been successfully used for designing computerized support within clinical settings. UCD is an iterative design process that involves users through a series of research and design activities to create usable designs [79]. CSCW researchers have applied UCD methods such as interviews, surveys, and participant observation to design support tools for medical personnel in a range of settings. For example, UCD was used in designing MediSenseView [67], a clinical-data interface system for resuscitation teams; SMILY [17], a system that assists pathologists interpret medical images; and a Breast Screening-AI system that helps radiologists screen for breast cancer [19].

Previous CSCW research has proposed and implemented several types of computerized support to address the challenges of maintaining awareness in complex teamwork, including information displays, cognitive aids, alerts, and ambient displays. For example, the use of visual displays like AwareMedia [8] in operating rooms has successfully supported awareness of the team- and patient status, leading to better coordination of work. McGeorge et al. [59] similarly developed an emergency department information system that represented time in a timeline view, allowing clinicians to quickly see patient flow and waiting room times. Participants who used the new display showed improved situational awareness [59]. Parush et al. [68] developed a cognitive aid to support situational awareness during emergency department resuscitations. This cognitive aid featured patient vital signs, present staff members, a log of orders, alerts, medication actions and tests, and a visual timeline displaying key events [68]. Although this display supported temporal and situational awareness during resuscitations, its alerts did not reach all team members because not all team members could look at the display during patient care.

Many studies designing and evaluating alerts in medical settings focus on improving actions such as prescribing medication [62] or accurately diagnosing patients [18][20]. To our knowledge, no alert systems have been developed that specifically support team delay awareness. A key challenge in designing an alert system for complex teams performing time-critical work is ensuring that alerts reach all team members. Complex teams include multiple members, each with different roles and responsibilities. In trauma teamwork, a surgical team leader may need one kind of information, while bedside nurses require another [12]. It is critical to understand the needs of each role through user-centered research activities.

An additional challenge for the design of alert systems is alert fatigue. Clinicians in emergency medical settings are concerned that information displays will cause distraction and hinder situational awareness [45], while additional alarms will cause alert fatigue [38]. To address alert fatigue, researchers have evaluated several methods to non-intrusively display information through ambient displays [24][38]. Guerra et al. [38] for example, evaluated the use of peripheral interaction to silence alarms via foot pedal or voice command in a neonatal intensive care unit. Other types of peripheral interaction, like ambient lights, can also serve as an alerting mechanism to convey information without perceived distraction [24]. Davis et al. [24] introduced a bidirectional ambient display to support activity awareness for the elderly and their caregivers. The ambient light speed and color changed based on the user's activity level. For example, if the user began walking or moving between rooms, the flashing of the ambient light would accelerate, improving social and activity awareness between the parties. Wallbaum et al. [80] developed "SocialFlower," a tangible display system that supports social and contextual awareness. The "SocialFlower" displayed different colors to represent activity levels and allow users to interact with each other via touch sensitivity. These prior studies have found that ambient displays can support users in a non-distracting and pleasant manner. However, the use of ambient displays as a mechanism for improving temporal awareness in time-critical *ad hoc* teamwork has not been explored yet.

In this paper, we iteratively designed and evaluated a prototype alert system that allows all team members to become aware of delays. This design and evaluation process has allowed us to better understand how teams in a complex work environment mitigate delays. We contribute a proof of concept for a prototype alert system to support delay awareness in complex teamwork and four mechanisms through which teams mitigate delays.

3 STUDY OVERVIEW

This mixed-methods study took place at the level I trauma center of an urban, pediatric teaching hospital in the mid-Atlantic region of the United States from October 2020 to June 2022. The study involved multiple data collection approaches. First, we interviewed seven clinicians to understand how teams experience delays. From these results, we derived the five most common delays during trauma resuscitation, the perceived causes, and how different roles on the trauma team experienced and managed delays. We then ran five card-sorting workshops with 11 participants to further discuss and prioritize delays. After prototyping the alert system, we evaluated its perceived usefulness in detecting delays using near-live, video-guided simulations. The hospital's Institutional Review Board (IRB) approved this study. Below we describe the research setting and participants and present the results of user and design research and system evaluation.

3.1 Research Setting

Trauma resuscitations at our research site are performed by a medical team comprising multiple specialties, including surgery, emergency medicine, anesthesiology, nursing, respiratory therapy, pharmacy, social work, and child life. Each member performs a specified task to evaluate and manage the injured child or adolescent using the Advanced Trauma Life Support protocol [3]. The most experienced clinicians (e.g., surgical fellow/attending and emergency medicine fellow/attending) and the most experienced nurses (e.g., charge nurse, nurse shift coordinator) comprise the leadership team that receives and interprets the information from providers evaluating the patient (e.g., surgical resident, nurse practitioner, respiratory therapist, bedside nurses). We refer to team members who actively evaluate the patient as "activity performers." Team members tasked with interpreting information and planning the next phase of care are referred to as "activity leaders." We did not study providers that assist the team in tasks (e.g., anesthesiology) or in the patient's social needs (e.g., social work).

Table 1: Participant breakdown for user research activities: participant ID, team role, performer or leader, years of experience in trauma resuscitation, and user research sessions in which they participated.

ID	Trauma Team Role	Activity Performer (P) or Leader (L)	Experience	Semi-Structured Interview	Card Sorting Workshop #	Near-Live Simulation
P1	Surgical Resident	P	4 months	Yes	-	-
P2	Surgical Resident	P	3 months	Yes	-	-
P3	Nurse Practitioner	P	5 years	Yes	-	-
P4	Emergency Medicine Fellow	L	2 years	Yes	-	-
P5	Nurse-Shift Coordinator	L	4 years	Yes	5	Yes
P6	Nurse - Shift Coordinator	L	2 years	Yes	4	-
P7	Attending Physician	L	13 years	Yes		Yes
P8	Attending Physician	L	3 years	-	3	Yes
P9	Pediatric Emergency Medicine Fellow	L	2 years	-	4	
P10	Nurse Practitioner	P	13 years	-	-	Yes
P11	Bedside Nurse	L	5 years	-	2	-
P12	Bedside Nurse	L	4 years	-	5	-
P13	Surgical Resident	P	5 years	-	-	Yes
P14	Pediatric Medicine Fellow	L	3 years	-	5	-
P15	Pediatric Emergency Medicine Fellow	L	3 years	-	3	-
P16	Charge Nurse	L	18 years	-	1	-
P17	Attending Physician	L	7 years	-	-	Yes
P18	Attending Physician	L	4 years	-	2	Yes
P19	Attending Physician	L	4 years	-	1	Yes
P20	Charge Nurse	L	5 years	-	2	Yes
P21	Surgical Resident	P	4 years	-	-	Yes

Each trauma bay is equipped with medical tools, instruments, and other artifacts that support temporal, situational, and process awareness. Constantly changing vital sign monitors communicate patient status, and paper and digital checklists support protocol adherence. The rooms also have two types of clocks to support temporal awareness: traditional clocks and stop clocks. Traditional clocks display the absolute time, which requires team members to perform mental calculations to determine the duration of activities [52]. Stop clocks represent the time since the resuscitation started. At our research site, teams are instructed to manually start a stop clock by pressing a button at patient arrival and then turn it off at the end of the resuscitation. The main trauma bay is equipped with three video cameras set up at different angles to provide the top and side views of the patient and team. Recorded videos are used for quality improvement purposes and can also be reviewed for research purposes after consent is obtained from the patient's parent or caregiver.

3.2 Participant Recruitment and Demographics

Study participants across all research activities were recruited to represent the core trauma team members. Recruiting research participants in this setting is challenging because clinicians have busy schedules and work across multiple units and shifts. The COVID-19 pandemic further exacerbated the recruitment challenges because it led to provider fatigue and patient overload, leaving little time and interest for participation in research. To overcome these challenges, we relied on research coordinators at our research site to reach out to potential participants in person and through internal mailing lists. User research involved 21 participants (Table 1) and design research involved 27 survey

Table 2: Design survey participant breakdown: Participant ID, team role, role type (performer or leader), and years of experience in trauma resuscitation.

ID	Trauma Team Role	Activity Performer (P) or Leader (L)	Experience
SP1	Attending Physician	L	N/A
SP2	Attending Physician	L	4 years
SP3	Attending Physician	L	30 years
SP4	Attending Physician	L	3 years
SP5	Attending Physician	L	13 years
SP6	Attending Physician	L	3 years
SP7	Attending Physician	L	4 years
SP8	Attending Physician	L	12 years
SP9	Attending Physician	L	N/A
SP10	Attending Physician	L	18 years
SP11	Attending Physician	L	2 years
SP12	Attending Physician	L	14 years
SP13	Attending Physician	L	N/A
SP14	Attending Physician	L	28 years
SP15	Attending Physician	L	13 years
SP16	Attending Physician	L	N/A
SP17	Bedside Nurse	P	24 years
SP18	Bedside Nurse	P	N/A
SP19	Charge Nurse	L	3 years
SP20	Charge Nurse	L	10 years
SP21	Nurse - Shift Coordinator	L	6 years
SP22	Nurse - Shift Coordinator	L	3.5 years
SP23	Nurse Practitioner	P	4 years
SP24	Pediatric Emergency Medicine Fellow	L	7 months
SP25	Pediatric Emergency Medicine Fellow	L	2.5 years
SP26	Pediatric Emergency Medicine Fellow	L	N/A
SP27	Medication Nurse (Pharmacist)	P	4 years

participants (Table 2), for a total of 48 study participants whose trauma resuscitation experience ranged from several months to more than 10 years. All user sessions were conducted remotely over Zoom and recorded to facilitate the analyses. All participants in user research activities received monetary compensation for their time, while survey participants were entered in a drawing for one of three $30 Amazon gift cards. Several clinicians participated in multiple user research activities, allowing for a longitudinal perspective. Because the survey was anonymous, we could not determine if any of the survey participants took part in other research activities.

4 USER RESEARCH TO INFORM THE DESIGN OF A PROTOTYPE SYSTEM

4.1 Semi-Structured Interviews to Elicit Delay Experiences

4.1.1 Methods. To answer our first two research questions—"What are the most common delays in emergency medical care?" and "How clinicians experience these delays and become aware of them?"—we conducted hour-long interviews with seven clinicians who had participated in trauma resuscitations at least once a week. The interviews were designed as a combination of semi-structured and stimulated recall interviews. The interview questions focused on discussing common delays, the communication mechanisms used during delays, delay management techniques, and alert preferences. For example: "What kinds of delays do you experience?" "How do you know there is a delay?" and "When and how do you communicate about the delay?"

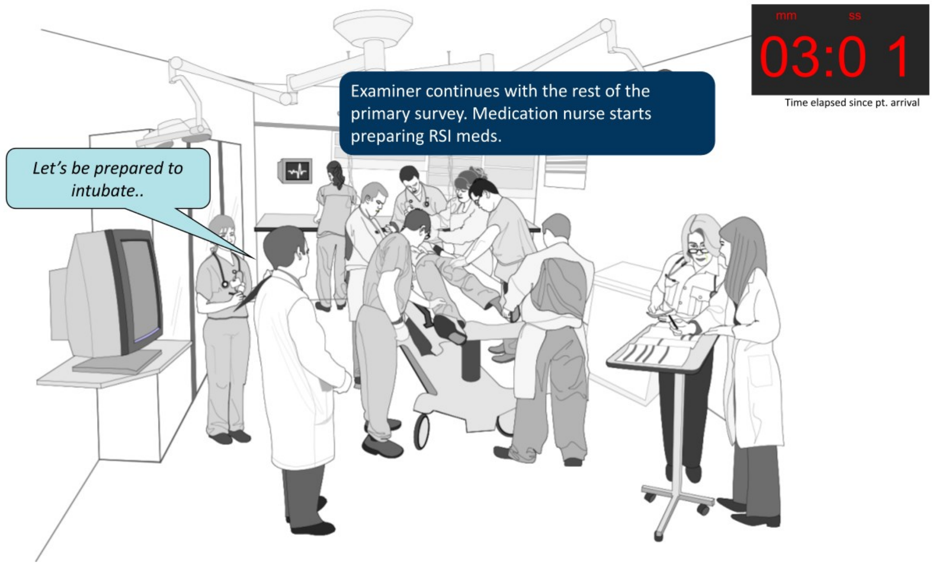

Figure 1: An example slide from the visual prompt used in situated recall interviews, showing a trauma team at minute three of the resuscitation when the leader requested the team to prepare for intubation.

Stimulated recall helps participants retrieve memories of past experiences [25]. Because trauma team members may respond to multiple resuscitations in a single day while also taking part in other types of patient care, this approach helped our participants recall specific experiences. Previous studies in clinical contexts used videos of procedures for stimulated recall interviews [42]. At our research site, however, the approved IRB protocol does not allow individuals to watch recordings of prior procedures if they did not participate in those events. Instead, we developed a visual prompt based on an actual resuscitation case using timestamps of events, a narrative of the activities, team communications, and illustrations of the trauma bay. During the simulated recall activity, the interviewer narrated through the visual prompt and elicited participant reactions to non-routine events. As we narrated through the prompt, we asked the participants to tell us if they noticed anything atypical such as a delay or error (Figure 1). Once a participant noted any issues, we further probed about the frequency of the issue, what actions they would take, and what they would do differently. At the end of the simulated recall, we asked the participants to discuss their ideal solutions for reducing delays and the types of alerts they would prefer.

Two doctoral researchers trained in HCI reviewed and corrected the Zoom-generated transcripts. Using a qualitative content analysis approach, we identified themes using NVivo, a qualitative data analysis software. Both researchers conducted open coding on the transcripts to identity common themes. The researchers then compared their codes and discussed the emerging themes until reaching a consensus. Inter-rater reliability was not used because it is not required in qualitative content analysis [66].

4.1.2 Findings. From the interview sessions, we identified the five most common delays in emergency medical care: (1) delays in the initial intravenous (IV) access attempt and placement, (2) delays in obtaining the initial set of vital signs, (3) delays in obtaining an updated blood pressure, (4) activity delays because time is misperceived, and (5) delays in the time from a request to perform a task to actual task performance. We also elicited perceived causes for these delays and how different roles on the trauma team experienced and managed delays.

Common Delays during Trauma Resuscitation. The most frequently mentioned delay was in obtaining the initial intravenous (IV) access. Five participants described how they frequently experienced this delay during trauma resuscitation. The participants also emphasized the importance of this procedure because other activities such as intubation and medication administration depend on timely IV access [P4, P5, P6]. Of the five participants who described delays in obtaining IV access, four mentioned that the team should have switched to establishing intraosseous (IO) access—an alternative method to provide fluids, medications, and blood products directly into the bone marrow—to speed up the process [P2, P3, P4, P6]:

> "There is a hesitancy for placing faster IV access here. [We need to be] educating nurses if IVs are taking a long time, we need to switch to something that will give us access faster." [P2]

Four participants also discussed delays in obtaining vital signs. A shift coordinator described:

> "I have had delays in people waiting to get a BP (blood pressure). People will be in the bay and trying to get a manual BP... trying to get a pulse. I've seen people spending a lot of time trying to get that number when they should be treating hypotension... If you're not getting a number, it's probably not good." [P5]

Some participants described general delays, like activities taking longer than usual (3/7) and clinician requests taking long to complete (3/7). One surgical resident described a case where she urged the team to act faster: "*We said CT scan seven minutes ago and we don't have it yet. What can I do to speed that up?*" [P2].

Perceived Causes for Delayed Activities. The participants described that a common cause for these delays is a lack of situational and temporal awareness. They discussed how activity performers often experience "tunnel vision" and lack awareness of how much time has passed, e.g., "*People think in a black hole with blinders on and don't realize how much time has passed*" [P2]. Another surgical resident explained:

> "I never check the clock. Maybe I should. There's just an order to how I was trained and that's how I go by it... I don't keep track of time." [P1].

This lack of temporal awareness can also lead to the lack of awareness of delays. For instance, a clinician may attempt an activity for over five minutes without realizing how much time has elapsed. Instead, clinicians should stop the activity and ask for assistance or use a different method.

While discussing tunnel vision, one participant brainstormed potential approaches for increasing temporal awareness:

> "Nurses can get tunnel vision and have no idea how long they're taking to establish the access. Just by saying 'Five minutes have gone by,' '10 minutes have gone by,' the team can re-evaluate themselves, 'why hasn't this happened yet?' It's really easy for time to just stop while you're there. If you had a reminder of time elapsed, it cues people back in and maybe back on their toes." [P5]

The participants also discussed an incomplete activity alert. A charge nurse described:

> "Maybe like a loud alarm that would go off if something has been skipped. Something like 'this activity has not been done.' If you set a time alert and it was like 'it's been 10 minutes and the patient hasn't been intubated,' but what if the patient doesn't need to be? It's hard to make it a time alert. It's more of an order thing." [P7]

This nurse felt that alerts sounding or appearing at a specified time interval may only be appropriate for some cases. Instead, they recommended a system that detects when an activity request is ignored or a step in the process is skipped and then alerts the team.

Delay Experience and Management for Activity Performers vs. Activity Leaders. Activity leaders are not directly involved in hands-on patient care, which allows them to keep track of time, assist with estimating time for activity performers, and alert about incomplete or delayed activities. In contrast, activity performers are "*heads down*" and focus on evaluating the patient, which makes referrals to visual timekeeping artifacts more challenging. Illustrating this point, a participant stated:

> "I look at the clock on the wall 10 times before the patient arrives and then when the patient arrives, I never look at it unless we're standing around waiting for something, like waiting for the blood pressure cuff" [P2].

Activity leaders in our interviews were aware that performers cannot monitor the timekeeping artifacts in the room. They shared a concern that another display for alerting the team to delays would not help draw the team's attention. One of the nurse documenters explained, "*No [activity performer] is looking on the wall in the middle of a bloody case*" [P3]. Instead of looking up or around, activity performers focus on the task at hand and rely on the leaders to keep time, monitor progress, and provide alerts. A junior resident described:

> "I can't say I look at it [the clock] that often, but I think those in the supervisory role are paying attention. The nurse who is keeping track of time will let us know how we are doing." [P6]

From participant experiences with the five most common delays, we identified seven possible alerts for further exploration: (1) IV access has not been established (after a certain amount of time), (2) IV access has been attempted multiple times – switch to IO?, (3) No blood pressure for over 3 minutes, (4) No vitals for over 3 minutes, (5) Current activity is taking more time than usual, (6) "X" activity was requested 5 minutes ago and has not yet begun, and (7) Time interval alert - an alert every five minutes after patient arrival.

4.2 Card-sorting Workshops

We conducted card-sorting workshops to determine if the interview findings generalized across team roles. We also used these workshops to answer our third research question: "What are potential visual mechanisms for communicating delays to clinicians?"

4.2.1 Methods. We conducted five hour-long card sorting workshops with a total of 11 participants, each involving two to three different team roles. The workshops focused on (1) understanding how different team roles prioritize delays and alerts, and (2) eliciting design requirements for the prototype alert system. The workshops combined a card-sorting activity [72] and a semi-structured group discussion. Previous work on health information technology design has used card sorting experiments to understand user priorities and develop user interfaces [30][73]. In the context of our domain, the card sorting approach was helpful in visualizing the participants' alert priorities before and after discussion with their colleagues.

In addition to participants, each workshop involved three to five researchers. One researcher led the workshop, facilitating the introductions and group discussion, while the other researchers took notes and supported individual card-sorting activities during the breakout sessions. We started each workshop by introducing the study, obtaining consent to record the session, reviewing the results from the semi-structured interviews (five common delays and seven alerts), and asking for participant introductions. Each participant then entered a break-out room with a researcher to

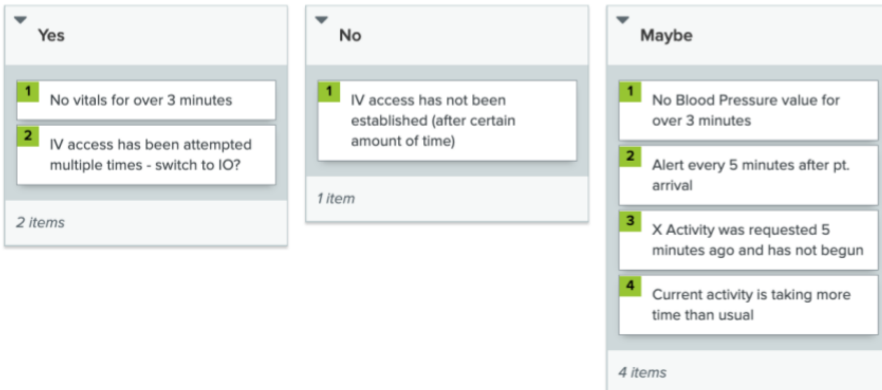

Figure 2: A screen capture of the OptimalSort interface used during card sorting workshops, showing the results of the group sorting activity from Workshop # 4. The alerts on the left were preferred by all members of the group. The alerts in the middle were rejected by all group members. The alerts on the right were considered but no group member expressed strong preference for any of the alerts.

complete an individual card-sorting activity. We used OptimalSort, an online card-sorting interface, to conduct card sorting (Figure 2). Each participant was asked to sort the seven alerts into three categories: "Yes," meaning they preferred this alert, "No," meaning they did not prefer the alert, and "Maybe," meaning they were not certain, or it would depend on the design. The participants were instructed to talk aloud about their decision-making process and explain alert preferences. After completing the sorting activity, we asked the participants to rank the alerts in the "Yes" category and explain their reasoning.

Next, the participants returned to the main Zoom room for a semi-structured group discussion about alert preferences based on team roles. We shared the results from individual card-sorting activities, with a similarity matrix showing where participants within each group agreed and disagreed. We then asked the participants to discuss why their opinions differed and how their role affected their decisions. The participants sorted and prioritized the alerts again, deciding as a team and reconciling individual differences. In the final portion of the workshop, we asked the participants to brainstorm design ideas for the alerts they had prioritized. The participants shared and discussed these design ideas and then shared feedback on each other's ideas.

We manually corrected Zoom-generated transcripts from all workshops. Two researchers on the team, a doctoral student studying HCI and a second-year medical student who had assisted in facilitating the workshops, performed qualitative content analysis. For each workshop, the researchers read through the transcript and used open coding to assign different themes. They compared their themes and reconciled them into a unified list through discussion. We also compiled the common design ideas into a list of design requirements for the prototype alert system.

4.2.2 Findings. We first present user priorities and preferences for the delay alerts, including the differences between individual and group priorities. We then describe the design requirements for the alerts.

User Priorities and Preferences for Alert Types: The individual card-sorting activities showed that most participants found only two of the seven alerts useful: "No vitals for over 3 minutes" and "IV access has not been established." These alert preferences were also confirmed during group discussions and group sorting activities: participants ranked the "No vitals for over 3 minutes" alert as the most important in three workshops, while "IV access has not been established" and "Activity was requested 5 minutes ago and has not begun" alerts were each ranked as most important in the other two workshops.

A major area of disagreement across roles was around the vital sign alerts. Most nurses sorted the "No blood pressure value for over 3 minutes" alert into the "Yes" category, while most physicians and fellows sorted this alert into "Maybe" or "No" categories. During group discussions, the physicians acknowledged the importance of this alert for other roles but argued it should be combined with "No vitals for over 3 minutes" to avoid redundancy. Most participants also felt that "IV access has not been established" and "IV access has been attempted multiple times – switch to IO" were redundant and proposed combining the two.

Five of the 11 participants sorted the time-interval alert into the "Yes" category and four participants sorted the alert into the "Maybe" category. Four of the five participants that preferred the alert were "activity performers" and thought that the alert would improve their temporal awareness during patient evaluation. Two participants that sorted the time-interval alert into the "No" category were attending physicians. After group discussion, most workshop groups sorted the time-interval alert into the "Maybe" category because they thought its usefulness would depend on the alert design:

> "I like the idea of the clock changing, because maybe then, like, yes, there is a clock in that room. However, I would say that I'd be interested to take a poll of the people who are in the room who actually pay attention to it" [P5].

The "Current activity is taking more time than usual" alert was least preferred. During individual sorting, most participants sorted it into the "Maybe" or "No" category. They felt this alert was like "X activity was requested 5 minutes ago and has not begun" and it was unclear what actions they would take with the alert information. This result held with the group sorting activity as it was the only alert not receiving a "Yes" during the group sorting.

The group discussions helped us determine the similarities and differences in role preferences. If any participant voiced strong support for an alert, the others would acquiesce to their expertise, agreeing to have the alert and assuming the alert would remain unintrusive. For example, an attending physician said in response to a nurse supporting the "No vitals for over 3 minutes" alert: "*I totally respect and appreciate [participant's] input on all of this... I think if they would benefit from this alert – we should have it"* [P18]. Overall, the participants preferred fewer and less frequent and agreed to combine or eliminate unnecessary alerts. For example, all workshops agreed to select either "No vitals for over 3 minutes" or "No blood pressure for over 3 minutes" as their highest priority, assuming the two would be combined. A similar agreement was made for "No IV access for over 5 minutes" and "Multiple IV attempts have been made – switch to IO?" alerts, where all workshop groups agreed that only one of these was needed.

Design Requirements for Delay Awareness. Most participants (9/11) preferred visual alerts over audible or vibrating alerts because visual alerts were perceived as less interruptive than others. Three participants preferred visual cues such as a "*quick pop up*" or a banner on a room monitor to avoid blocking other information. One ED fellow explained:

> "A display won't disrupt the flow of the team. But someone would be getting these alerts and then relaying them to the rest of the team" [P9].

Nine participants thought that audible alerts would be inappropriate for a dynamic medical setting such as trauma resuscitation. They were concerned that audible alerts would only contribute to the room's noise and overall sense of panic. A charge nurse explained, "*I'm totally against audible alarms. Horns or anything like that wouldn't do anything except irritate people*" [P5]. Instead, the participants (three nurses and one fellow) agreed that audible alerts should only be used in high-acuity scenarios where team members could not look away from the patient. Two participants indicated that audible alerts should be verbal or "*personal*" alarms. An ED physician described:

> "Something in a pocket that beeped just for me to hear or vibrate would be appropriate because I do not want it to be interrupting people who are in the middle of a task" [P8].

Six participants, including three charge nurses and three ED physicians, envisioned an information display that (1) provides enough information to convey that a delay is occurring and (2) makes the type of delay visible to all team members. A charge nurse explained:

> "I envision it being some sort of a screen device that all can see, and we're not disturbing the rest of the room… It'll turn a different color once that you see that request on the screen. It alerts us to bring the team in, figure out if there is a delay, and move on" [P6].

Four other participants, including three activity leaders, brainstormed color-changing displays with "*a color changing on the clock*" [P15] or "*a screen that populated outstanding orders*" [P9] with colors based on urgency. Each participant highlighted the need for a system that non-intrusively provides high-level information about delays to the whole team.

Clinicians also expressed several concerns about alerts. Four participants, all attending physicians, were concerned that alerts would be a nuisance during procedures. One physician explained, "*I have trouble thinking of activities that would be a useful alert as opposed to a nagging alert I would just want cleared"* [P8]. Eight participants voiced concerns that another alerting system would add to alarm fatigue, a common concern in health information technology research [38]. When clinicians receive too many unhelpful alerts, "*people start to ignore alerts*" [P7]. The same ED attending continued:

> "I'm a minimalist, I don't believe in having alerts unless they're going to really add a lot and change how I clinically manage patients. I don't believe in having more alerts, I think that just leads to more alarm fatigue. And at the end of the day, nobody is going to pay attention, or they become more of an annoyance." [P7]

The card-sorting workshops highlighted three major design requirements for our prototype alert system: (1) alert all team roles, (2) avoid alert fatigue through proper timing and frequency of alerts, and (3) rapidly convey information without too much detail.

5 DESIGN RESEARCH: THE PROTOTYPE ALERT SYSTEM AND ALERT ICONS

5.1 The Prototype Alert System: Design Process and System Overview

Informed by the interviews and card-sorting workshops, we derived four alerts for prototyping: (1) "No IV Access," (2) "Incomplete Request," (3) "No Vital Signs or Blood Pressure," and (4) the time interval alert. These final four alerts were adapted from the most prioritized alerts during the workshops and combined several alerts based on user feedback.

We began an iterative sketching process for the alert system using the three design requirements. First, we used the 10x10 sketching technique [13] in which we sketched 10 different high-level concept ideas for an alerting system and then sketched 10 more ideas for each iteration. We discussed each design idea and compiled preferred features into five different ideas. These five ideas were discussed with the medical experts on our team before re-sketching based on their feedback.

Figure 3: Components of the finalized prototype alert system. Left: A collage showing the system overlaid on top of a simulation video to illustrate the system (grid with alerts and ceiling lights] in the room. Right: A zoomed-in grid component showing the alerts for No IV access (upper left), No vital signs (upper right), Incomplete request (bottom), and Time interval (center).

After three rounds of sketching and ideation, we arrived at a grid concept where multiple alerts could be simultaneously displayed through icons (Figure 3). The central area of the grid displays a clock showing the elapsed time. When a new alert is triggered, the corresponding icon appears and lights up in one of three grid areas (Figure 3, right). To alert activity performers, we developed a concept of lights around the ceiling that light up with the grid (Figure 3, left).

We repeated the 10x10 sketching exercise to design the icons that would accurately represent each type of delay and its corresponding alert. After presenting the ideas to the research team, we finalized three to eight icons per alert and solicited feedback through a design survey.

5.2 Design Survey to Determine Icon Designs for Delays and Corresponding Alerts

5.2.1. Methods. We administered an online survey to collect additional data for our third research question: "What are potential visual mechanisms for communicating delays to clinicians?" The survey participants were recruited from our research site via emails sent to listservs for nurses, ED attending physicians, and surgical residents. A total of 310 clinicians received the call for participation and 27 responded (Table 2). We piloted the survey with three medical experts on our team to ensure clarity of questions and appropriate duration.

The survey was administered using Qualtrics and took about 10 minutes to complete. The survey was divided into four sections. First, the participants were asked about their team role and years of experience. Next, the survey summarized the four delays and associated alerts, and then showed 12 icons representing three of the four alerts: "No IV Access," "Incomplete Request," and "No Vital Signs or Blood Pressure." The participants were asked to type in what they thought each icon represented. The fourth timer alert was not included in the survey because it was not represented by an icon. Each alert was then explained in the following section, along with the correct icon. Participants were asked to select the icon that best represented the alert and explain their selections. The survey also asked about potential design improvements for each alert. Lastly, the survey presented an overview of the prototype alert system and asked for participant feedback. All questions were in a free-text format. The survey was anonymous and asked for the participant contact information in an unlinked question for the raffle.

Figure 4: Icon designs for the "No IV access" alert.

5.2.2. Findings. The icons for the "No IV access" alert (Figure 4) had the highest recognizability. Forty percent (n=12) of the participants correctly identified Icon B, while 36.6% (n=11) of the participants correctly identified Icon A. In contrast, when asked which icon best represented this alert, 60% (n=18) of the participants said they preferred Icon A because they did not like the large "X" across the fluid bag. Eight participants thought the bag looked like a blood bag rather than an IV fluid bag. Four participants recommended adding an "IV needle" or using the letters "IV" as part of the icon design. An ED attending wrote that "*B looks more like the IV is not working*" [SP6] and a bedside nurse wrote, "*B looks like it's a clinical instruction not to give blood* [SP17].

The next most recognizable icons were for the "No vitals or blood pressure" alert (Figure 5). Icon A was the most recognizable, with 16.67% (n=5) of the participants correctly identifying the alert. Icon B was correctly identified by 10% (n=3) and Icon C by 13.33% (n=4) of the participants. When asked which of the three icons best represented the alert, 37% (n=11) of the respondents chose Icon B, 27% (n=8) chose Icon C, and 20% (n=6) chose Icon A. Two participants wrote "*None*." The participants chose Icon B because it was the "*cleanest*" icon. An emergency attending wrote that "*B is a clear visual,*" but that, "*The cross is confusing*" [SP1]. Another attending wrote, "*This actually looks like a vital sign monitor*" [SP10]. When asked how they would redesign the icon for this alert, most proposed modifying Icon B by removing or increasing the size of the "X" sign.

The icons for the "Incomplete request" alert were the least recognizable (Figure 6). This finding is not surprising because this alert represents the most abstract concept. Four participants correctly identified Icon D (13.33%), while Icons A, B, C, and E were each correctly identified by only one participant. No participant correctly identified Icons F and G. Forty-three percent (n=13) of the participants preferred Icon B, and 20% (n=6) preferred Icons C and G each. The participants who chose Icon B liked its simplicity. The participants who preferred Icon G felt it was the most intuitive. Several participants proposed an exclamation point and text specifying the delayed activity for Icon G. This idea combines the simplicity of Icon B and intuitiveness of Icon G.

Across all alerts, the most preferred icons did not align with the most recognizable icons. Even after learning the correct meaning for all icons, the participants preferred icons with lower recognizability. This observation suggests that icon recognizability may not be the most critical factor for icon design in a dynamic medical setting. This implication will require clinicians to learn the alerts through training or on the job.

The participants valued "clean" designs and simple icons with visual details and more text. For instance, the participants recommended adding the letters "IV" to the "No IV access" alert and an

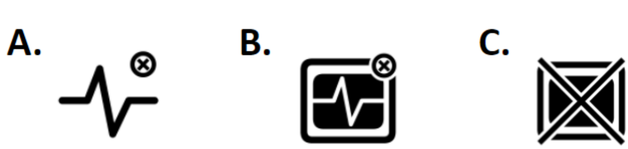

Figure 5: Icon designs for the "No Vitals or blood pressure" alert.

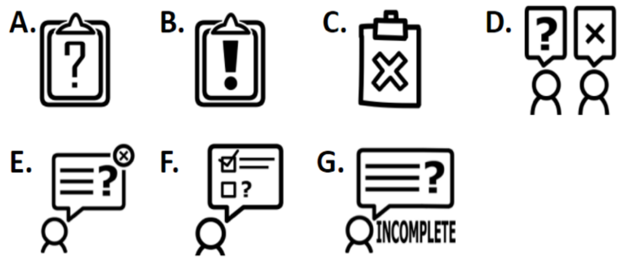

Figure 6: Icon designs for the "Incomplete request" alert.

activity label for the icons representing an incomplete request. Eight participants commented that adding an "X" sign to the icon design can add confusion. An attending wrote, "*The small X seems to indicate something that has not been done; the large X seems like something should not be done*" [SP10]. Other participants similarly thought the icon meant, "*Do not connect the monitor*" or "*There is no monitor connected to the patient.*" The presence of the simple vitals icon as an alert already informs clinicians that something is wrong. Adding "X" or "No" creates unnecessary confusion.

Based on the findings from this survey, we re-designed the icons to reflect the feedback (Figure 3). We removed any "X" signs from the icons and clarified the IV icon by adding the letters "IV." We selected Icon G for the "Incomplete request" alert but replaced the three lines with the specific text indicating the delayed activity.

6 EVALUATION OF THE PROTOTYPE ALERT SYSTEM

To answer our fourth and fifth research questions—"How do clinicians perceive visual representations of delays?" and "How do clinicians react to and mitigate delays?"—we conducted an evaluation study using video-guided, near-live simulations. We next describe our experiment design, metrics, approaches to data analysis, and findings.

6.1 Methods

6.1.1. Experiment Design. Our ultimate goal is to implement this alert system in real-world patient care. Before investing into further development, we needed an approach that could objectively assess the system's perceived usefulness and elicit user reactions to delays. The constraints of the COVID-19 pandemic, limited resources, and recruitment challenges make the real-world simulations unfeasible without first validating the proof of concept.

To provide evidence that our prototype alert system warrants further development and introduction into the resuscitation environment, we conducted near-live, video-guided simulations with 10 clinicians (Table 1). This approach closely mimics clinical workflows by having participants watch video clips of clinical scenarios and simultaneously use systems to evaluate their usability [54]. Using a "think aloud" protocol, near-live scenarios can elicit rich information on the user's thought process [54]. Unlike live simulations, near-live simulations allowed us to observe delay response and mitigation strategies because the participants were instructed to think aloud and verbalize their decision-making processes. Near-live simulations can also save resources and time by creating appropriate abstractions of environments and processes rather than exactly replicating them [63]. Prior research has shown that near-live simulations provided an immersive experience for the participants and achieved similar results as live simulations [54][73]. Our near-live simulations were also similar to "telesimulations," remote medical training protocols used when teaching resources are scarce [27][46]. A clinical trial has shown that "telesimulations" are as effective as live simulations and traditional training methods in achieving learning outcomes [46].

We used video recordings from a prior study at our research site to develop evaluation scenarios that used real-world simulations. We selected two simulations that were used as controls (i.e., trauma teams were directed to perform resuscitations as usual) and that involved several process delays. A medical expert on our team reviewed both videos, marking the start and end times for each delay and noting other attributes, such as types of delays and how long they lasted. We used this data to (1) set up our experimental and control scenarios and (2) as our ground truth in later analysis of participant performance. Both videos were 12-14 minutes long. In the first simulation video [Team E], the trauma team experienced one delay during patient intubation that would have triggered an "Incomplete request" alert for an incomplete intubation task. The team in the second simulation video [Team D] experienced two delays. The first delay was in establishing IV access that would have triggered the "No IV access" alert. The second delay was in administering blood that would have triggered an "Incomplete request" alert. We then edited both simulation videos with a functioning illustration of the prototype alert system (Figure 3, left). Using previously marked timestamps for each delay, we triggered the alerts in the grid display and ambient lights at those time points. The "Incomplete request" alert was activated five minutes after someone had requested an activity that was still pending. The "No IV access" alert was triggered after five minutes had elapsed and IV access was still missing or if five minutes had elapsed since an additional IV had been requested. The "No vitals or blood pressure" alert was triggered if five minutes had elapsed and vital signs were still missing. The "Time interval alert" lit up in yellow every five minutes following the patient's arrival.

During near-live simulations, the clinicians first watched the control version of the scenario (no intervention), followed by the experimental scenario (with the prototype alert system overlaid on top of the simulation video). Half of the clinicians had Team E video as the experimental scenario and Team D as the control scenario, while the other half had the Team D video as the experimental scenario and Team E as the control scenario. Each participant observed three delays that would have triggered an alert, leading to a total of 30 observations of delay experiences – 15 for the control scenario and 15 for the experimental scenario.

6.1.2. Procedure. Each near-live simulation lasted an hour and was conducted over Zoom. We first introduced the study and asked the participant about their role and how often they referred to displays in the trauma bay. We then presented an overview of the prototype alert system and explained all alerts they could potentially see during the session. We instructed the participants to watch two simulation scenarios and think aloud about what was happening in the simulation room. We also asked them to explain what they would do in response to team actions they observed, what they would say to different team members if they were in the room, and anything that came to mind while watching the simulations. In the end, we asked questions about their experiences in both simulations, whether they thought the prototype system would help improve their awareness of delays, and what feedback they had for our design. All sessions were recorded after receiving the participant's permission to record. The Zoom-generated transcripts were downloaded and manually corrected for analysis.

6.1.3. Measures and Data Analysis. We reviewed the videos of the control and experimental scenarios for all 10 participants to analyze their reactions to visual representations of delays and delay response times. In the experimental scenarios, we marked when alerts had been triggered. In the control scenarios, we marked when alerts would have been triggered. We then marked the time

Table 3: The participants' performance in detecting process delays with and without the prototype alert system and in responding to delays in scenarios with the system in place.

	Overall	Experimental	Control
Team E Scenario: "Incomplete Request" alert for a delayed intubation task			
Aware of Delay (# of participants)	5/10	4/5	1/5
Median Response Time to Delay	-	20 seconds	17 seconds
Team D Scenario: "Delayed IV" alert for delayed IV placement			
Aware of Delay (# of participants)	9/10	5/10	4/5
Median Response Time to Delay	-	20 seconds	60 seconds
Team D Scenario: "Incomplete Request" alert for delayed blood administration			
Aware of Delay (# of participants)	7/10	4/5	3/5
Median Response Time to Delay	-	16.5 seconds	47 seconds
All Three Delays			
Aware of Delay (# of participants)	21/30	13/15	8/15
Median Response Time to Delay	-	23 seconds	107 seconds

when the participants detected a delay was occurring. Example phrases that indicated delay detection included, "*Wow, this is taking a long time*" [P13] or "*Where's the blood*" [P21]. Two researchers independently marked the transcripts for delay detections and compared their results to ensure consistency. We calculated delay response time by subtracting the time when the participant noticed a delay from when the alert was or would have been triggered. In both scenarios, if a participant never voiced awareness of the delay, they received a time of "never," treated as a maximum value to allow calculating a median.

We also qualitatively analyzed the simulation transcripts using content analysis to understand how the participants responded to and mitigated delays. First, the two researchers independently reviewed each transcript, identifying themes about reactions to delays, alerts, and system design. The researchers then discussed the emerging themes and formalized a list of codes. Next, the researchers re-coded the transcripts using the formalized codes and then compared and compiled their results to finalize the themes.

6.2 Findings

6.2.2. Delay Awareness and Response Times. We found that the participants were more likely to detect delays in the scenarios with the prototype alert system than in the control scenarios (Table 3). The participants voiced awareness of delays in 86% (13 out of 15) of instances in the scenarios with the prototype alert system. In the control scenarios, participants voiced awareness of delays in just 53% (8 out of 15) of instances. When voicing awareness of delays, the participants in the control scenarios took longer to respond than the participants in the experimental scenarios. The median response time to a delay was 23 seconds in the experimental scenarios and 107 seconds in the control scenarios. These findings suggest that a live alert system based on this prototype could improve awareness of the most commonly occurring delays during trauma resuscitation.

6.2.3. Reactions to Delays. Our content analysis showed that the system's alerts prompted one of four events from the participants: "Perform/Request Action," "Perform/Request Modification," "Request Information," and "Report Progress" (Figure 7). The most common responses to a delay were requesting information (6/10) or reporting progress (6/10) shortly after a delay had been detected. A participant requested information when they needed more information before deciding on an action to mitigate a delay. For example, in response to the "No IV access" alert, an attending

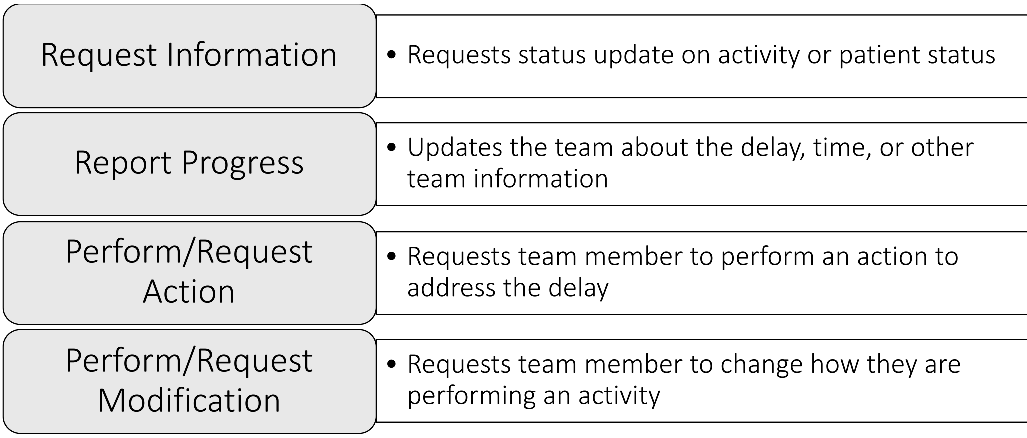

Figure 7: Participant actions prompted by the prototype alert system while responding to process delays.

said, "*If I saw the IV alert flash, I would have said 'do we have a line, or do we only have our IO,' which then would have clarified for the team... then I would refocus the team on that*" [P18]. The attending explained that this alert would have triggered them to gather more information about the status of the activity and then move on to an action to mitigate the delay. Another attending explained they would ask the team "*Is someone working on that?*" [P7] to determine whether any team member was actively working on the task or whether a further intervention was needed. Similarly, a surgical resident said they would "*want to know why it's taking so long*" [P13] and discuss any existing roadblocks with the team. A shift coordinator explained, "*If we see these [alerts] are going off, I will circle back and ask where we are at with that*" [P5].

Participants used the report progress event to inform the team about the patient's status. An attending described how she would have "*given another summary [to the team] about the patient*" [P19]. A shift coordinator said that the time interval alert would have triggered them to "*summarize [the activity so far], so this is where we're at, we have this plan moving forward, and what are our impending actions*" [P5]. Participants P7, P8, P10, P19, P20, and P21 stated they would share with the team that an alert indicating a delay had been triggered.

Sometimes the participants immediately worked to mitigate the delay by performing or requesting an action or performing or requesting a modification for an existing action. A surgical resident explained that after noticing the "No IV access" alert, they would announce to the room, "*We still don't have a guy working on [task]... we need to work on getting it*" [P13]. After noticing the "Incomplete request" alert about delayed blood transfusion, an attending said they would "*redirect them to the primary low blood pressure at this point to try to focus on the hypotension*" [P19]. A nurse practitioner described that if they were alerted of an IV access delay, they would "*just jump right to an IO*" [P10], a more invasive but quicker method for establishing IV access.

Activity leaders most frequently requested information to receive status updates from activity performers (Table 4). Activity performers requested information less often because they were busy completing the activity. The frequency of the other two mitigation mechanisms was consistent between activity performers and leaders. The next most frequent mechanism was "Report progress," followed by "Request action and modification" (Table 4).

Eight out of 10 participants found the prototype alert system helpful in increasing their awareness of delays (Table 4). The participants thought that the time interval alert helped them keep track of

Table 4: The frequency of four delay response mechanisms across activity leaders vs. performers, and whether they perceived the prototype alert system useful or not.

	Delay Response				Perceived Usefulness		
Role Type	Report Progress	Modification	Action	Request Information	Useful	Not Useful	Neutral
Activity Performer	3/4	2/4	2/4	2/4	4/4	0/4	0/4
Activity Leader	3/6	2/6	2/6	4/6	4/6	0/6	2/6
Total	6/10	4/10	4/10	6/10	8/10	0/10	2/10

time. A shift coordinator described, “*In a critical patient, sometimes you can lose track of time easily ... so I think these little cues could be helpful*” [P5]. An attending said the timing mechanism was helpful since team leaders could say, “*It's been X number of minutes since the patient is in here, and that can also really help the team*” [P19]. A surgical resident thought the time interval alert served a purpose for team leaders to say, “*Oh, it's been five minutes, and we still haven't even moved to the secondary survey”* [P13]. The time interval alert supported temporal awareness, reminding the participants of pending activities and to share information with the team. Participants P5, P8, P18, and P21 also commented that the time interval alert could support temporal awareness.

The other alerts on the grid were also found helpful, including the “Incomplete request” and “No IV access” alerts. An attending said, “*Especially from outside, watching the icons of what's actually missing helped because I had mistakenly thought [the patient] had another IV*” [P17]. Another attending thought the monitor alerts provided “*clarity on tasks that have not been done without having to look down at any papers or ask someone”* [P8]. A nurse practitioner similarly stated that the alerts would “*help the team leader maintain situational awareness as to priorities and getting the patient what they need quickly”* [P10].

All four participants in the activity performer roles favored the ambient lights that lit up alongside the alert grid. Two attending physicians were skeptical of this element [P7, P18], and a shift coordinator could not give an opinion because “*you never know until you see it in person*” [P5]. Activity performers perceived this element helpful. For example:

> “I like the idea of the light bar around the room because everyone else who's not standing at the foot of the bed where we are will see it too. Not that they need to look at the monitor even but, just like share awareness of what's going on” [P10].

This same participant later added, “*It's not just one person's job, but the whole team needs to be alert*” [P10]. A surgical resident shared similar thoughts:

> “At least for me as an evaluator, I don't really pay attention to [monitors] because you're focused on what's going on in front of you, however, if I could see it in the periphery, I would know what's going on” [P13].

Four participants, all in “activity leader” roles, found at least one element of the prototype alert system not useful, unclear, or distracting. A nurse practitioner thought the icon alerts were distracting because it took more mental effort to interpret an icon than to interpret the light, "*I guess just seeing it in the corner of my eye and trying to understand it versus the light*" [P5]. A charge nurse thought the lights and icons were both too general, stating "*The reminder doesn't really help if you don't know what the criteria is or what is missing*" and "*For someone to say it's been five minutes or 10 minutes, that doesn't really mean anything to me*" [P20]. However, following this statement, this same participant added, "*Well… I suppose it has been nine minutes and we're not at the secondary survey yet*" [P20]. Rather than prompting these participants to give summaries or check status updates, the alerts added confusion. One attending physician thought that the prototype alert system did not give enough information, "*Honestly, I was expecting more help out of that prompt thing… it didn't actually give me any information*" [P17]. Another concern from an attending physician was that the alerts would "*anchor the team leader to addressing those alerts over other sources of information they're getting*" [P8].

7 DISCUSSION

Our study has several implications for CSCW research and system design, including how computerized support can be designed to increase delay awareness in complex teamwork, as well as how complex teams respond to and mitigate delays.

7.1 Implications for CSCW Research

In this study, we aimed to design a prototype alert system to support delay awareness among clinicians working in a dynamic medical setting. By conducting user research with multiple roles, we were able to understand the information and alerting needs for different role types. A major challenge in designing technology for complex teamwork is ensuring that needs of all team members are met [8][52] . To design our system, we relied on two overarching role types found in both medical and non-medical team settings: activity performers (in our case, the clinicians who actively evaluate and treat the patient) and activity leaders (in our case, the clinicians charged with leading the team and/or documenting the team's progress).

Our findings suggest that activity performers require an alerting system that can quickly impart the minimum amount of information required to understand that a specific delay is occurring. In contrast, activity leaders require non-intrusive, but more detailed alerts that help inform the leader how best to mitigate an occurring delay. The debates during the card-sorting workshops on alert prioritization and alert format helped us determine the similarities and differences in how each role wanted information presented and then reach a preliminary design that addressed most of the needs of both role types. While we considered these two role types from a medical perspective, leaders and performers can be found in other collocated and distributed team-based domains such as search and rescue operations [47] and air traffic control [48]. For example, search and rescue operations are also high-stakes, time-sensitive events, while wilderness search and rescue teams (WSAR) are collaborative teams with performer and leader roles requiring different alert mechanisms from an alerting system [47]. WSAR performers—team members on the ground performing the search operations—may be more susceptible to time blindness like our activity performers in trauma resuscitation. Using an alert like our time-interval alert could improve their delay awareness. Additionally, alerts indicating that crucial steps of WSAR protocols have yet to be completed can trigger delay awareness among WSAR leaders and expedite mitigation strategies.

Our approach to understanding how complex teams mitigate delays could apply to WSAR and yield insights on how to improve teamwork and collaboration in this critical domain. Similarly, conducting near-live simulations that trigger delay detection in the domain of air traffic control could help researchers identify the mechanisms for delay mitigation used by different roles, further informing the technological or training needs.

We also found that leveraging icons could help meet the needs of both role types. These simplistic illustrations conveying complex information were appropriate for alerting clinicians of delays because the participants could quickly absorb the presented information with a glance. In addition, the ambient lights surrounding the workspace allowed for alerting activity performers of delays without requiring them to look up or take their eyes off the patient. We observed that icon recognizability was not the most critical factor when designing icons and that clinicians preferred cleaner and more simplistic designs, even if that meant more training. These findings suggest that icon simplicity may be preferred over its immediate recognizability in time-critical and team-based work settings.

Overall, our participants were more likely to detect a delay using our alert system in the experimental scenarios compared to their delay detection rates in the control scenarios. Both role types perceived the prototype alert system useful and thought the system would have made a meaningful clinical difference during actual resuscitations. These results, however, need to be considered against several study limitations. First, the user research components had small sample sizes that limited our ability to evaluate our findings and statistically generalize the results. Second, this study was conducted at one research site and the cultures and practices at other institutions could show different trends. For example, our prototype alert system focused on addressing the five most common delays we identified by interviewing clinicians at our research site. Other sites may manage other types of delays. Even so, the delays we identified are common in a range of dynamic medical settings, including the ICU and neonatal resuscitation, suggesting a broader medical applicability of our system [69].

In future work, we will evaluate a higher fidelity alert system in live simulations to measure the effects of the system on team performance and whether the alerts lead to faster delay mitigation. Observing the entire teams using the system in real time will yield more data about how teams work together to mitigate delays, as well as the effects of the system on their performance. Our delay response metric in this study depended on the participants consistently thinking aloud to capture their awareness of delays. While this approach allowed for insights into clinicians' thought processes and decision-making surrounding delays, a more realistic simulation would also allow for a more precise measurement of delay response times and awareness levels. Live simulations would also allow for better evaluation of the ambient light component. Now that we have shown the potential of this prototype alert system, we can use the insights and findings to further improve upon the alert designs and overall system design.

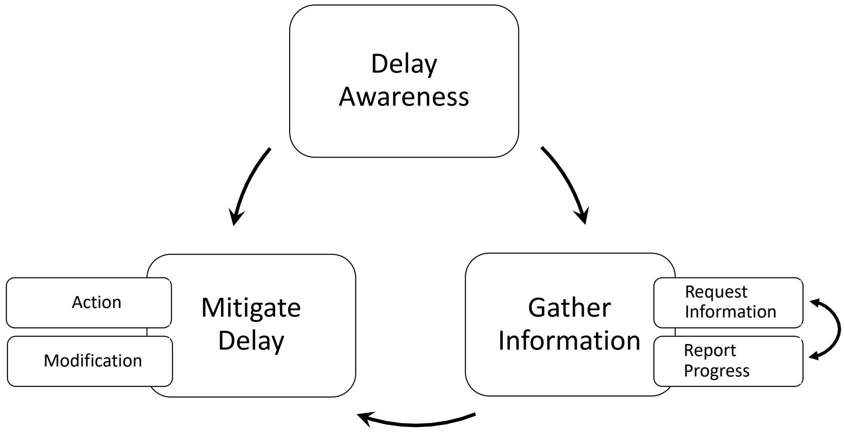

Figure 8: A graphical representation of the delay mitigation framework and the four mechanisms for delay mitigation.

7.2 Delay Mitigation Framework and Mechanisms for Delay Mitigation

By designing and introducing our prototype alert system to support delay awareness, we could pinpoint the moment a clinician detected the delay and then observe the actions they took once they attained awareness. Through analysis of the participants' reactions, we identified four mechanisms for delay mitigation in team-based dynamic work organized into a delay mitigation framework (Figure 8). The participants responded to delay awareness with one of four actions: request information, report progress, request/perform action, and request/perform modification. After detecting a delay, the participants would most frequently request information from activity performers or report progress on what has been achieved so far to *gather information* about patient and team status, or any roadblocks preventing the team from completing the activity. After the participants established sufficient situational awareness to understand what needed to be done to *mitigate the delay*, they would request or perform a new action or modify an existing action. Sometimes, the participants already had sufficient situational awareness after the alert to decide what actions to take to address the delay. In that case, they would immediately instruct the team to mitigate delay.

Previous research has described how trauma resuscitation teams respond to delays and other non-routine events by "compensating" and "acknowledging" the events [81]. Our mechanisms of delay mitigation further unpack *how* complex teams "acknowledge" and "compensate" delays by showing the specific actions they take. This overall framework for delay mitigation can now be used to further inform the design of computerized support for complex teamwork. Although we focused on designing a series of alerts to communicate different delay types, other approaches could provide support at the level of information integration at the critical junctures of the framework. For example, a system that continuously provides the updates about current team activity could support activity leaders in the information gathering step. Similarly, a system that recommends alternative steps to achieving an activity when a common route is not feasible could support activity performers when modifying an action.

The four mechanisms of delay mitigation can also be generalized to other complex teams, such as flight crews [26], air traffic controllers [48], and online role-playing game teams [55][64]. For example, we could see these mechanisms applying to Dismukes' [26] work on flight crew responses to challenging and stressful events. While Dismukes et al. studied how flight crew behaviors lead to delays and errors [26], identifying when and how flight crew use the four delay mitigation mechanisms could yield a better understanding of how to support flight crews and decrease the number of critical events. Another domain where delay mitigation mechanisms could be applied is online role-playing game (PRG) teams. Recently, CSCW researchers have studied how online game players work together to achieve game goals, focusing on the social behavior patterns [55][64]. As these teams also experience and mitigate delays during encounters, applying our delay mitigation framework may lead to new insights into players' social behaviors as they engage in online play. These examples illustrate the need for studying these mechanisms across domains to allow for a better understanding of how best to support complex teams and decrease critical delays and errors.

8 CONCLUSION

In this paper, we presented the findings from an iterative user-centered design process to develop a prototype alert system to support delay awareness in complex teamwork such as trauma resuscitation. We investigated (a) how different trauma team members experience delays, (b) differences in design preferences for an alerting system by team role, (c) clinicians' perceptions of icon designs representing delays, and (d) clinicians' responses to delays. To gain this understanding, we conducted a series of research activities, including interviews, a card-sorting workshop, an icon design survey, and video-guided, near-live simulations. As part of our contributions to awareness research, we created a proof-of-concept for a prototype alert system that triggers the detection of delays in complex teamwork and a framework with four mechanisms through which teams mitigate delays. Our future work will focus on developing a high-fidelity prototype that can be evaluated in real-world simulations and then implemented in patient care.

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REFERENCES

[1] Patricia S. Abril and Robert Plant. 2007. The patent holder's dilemma: Buy, sell, or troll? *Communications of the ACM*, Vol. 1, 36-44. http://dx.doi.org/10.1145/1188913.1188915

[2] Chitra Acharya, Harold Thimbleby, and Patrick Oladimeji. 2010. Human computer interaction and medical devices. *Proceedings of the 24th BCS Interaction Specialist Group Conference (BCS '10).* BCS Learning & Development Ltd., Swindon, GBR, 168–176.

[3] Advanced Trauma Life Support. 2018. Chicago, IL: American College of Surgeons.

[4] Joshua Avalos, Debrina Roy, Onur Asan, and Yiqi Zhang. 2021. The influential factors on nurses' situation awareness in inpatient settings: A literature review. *Human Factors in Healthcare* Vol. 1 (2021). http://dx.doi.org/10.1016/j.hfh.2022.100006

[5] Ian Akyildiz, Weilan Su, Yogesh Sankarasubramaniam, and Erdal Cayirci. 2002. Wireless Sensor Networks: A Survey. *Computer Networks*, Vol. 38, 4 (2002), 393–422. https://doi.org/10.1016/S1389-1286(01)00302-4

[6] David A. Anisi. 2003. *Optimal motion control of a ground vehicle. Master's Thesis.* Royal Institute of Technology (KTH), Stockholm, Sweden.

[7] Paramir Bahl, Ranveer Chandra, and John Dunagan. 2004. SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks. In *Proceedings of the 10th International Conference on Mobile Computing and Networking (MobiCom'04).* ACM, New York, NY, 112–117. https://doi.org/10.1145/1023720.1023742

[8] Jakob E. Bardram. 2000. Temporal coordination –on time and coordination of collaborative activities at a surgical department. *Computer Supported Cooperative Work (CSCW)* Vol. 9, 2 (2000), 157–187. http://dx.doi.org/10.1023/a:1008748724225

[9] Jakob E. Bardram, Thomas R. Hansen, and Mads Soegaard. 2006. AwareMedia: a shared interactive display supporting social, temporal, and spatial awareness in surgery. In *Proceedings of the 2006 20th anniversary conference on Computer supported cooperative work (CSCW '06).* Association for Computing Machinery, New York, NY, USA, 109–118. https://doi.org/10.1145/1180875.1180892

[10] Martina Buljac-Samardzic, et al. 2020. Interventions to improve team effectiveness within health care: a systematic review of the past decade. *Human Resources Health.* Vol. 18, 1, 1-42. https://doi.org/10.1186/s12960-019-0411-3

[11] Martina Buljac-Samardžić, et al. 2021. What do we really know about crew resource management in healthcare? An umbrella review on crew resource management and its effectiveness. *Journal of Patient Safety*, Vol. 17, 8. e929-e958. https://doi.org/10.1097/PTS.0000000000000816

[12] Barbara Burian and R. Key Dismukes. 2020. Why we fail to rescue during critical events. *Anesthesiology Clinics* Vol. 38, 727-743. https://doi.org/10.1016/j.anclin.2020.08.009

[13] Bill Buxton. 2007. *Sketching User Experiences: Getting the Design Right and the Right Design.* Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.

[14] Federico Cabitza, Carla Simone, Marcello Sarini. 2009. Leveraging coordinative conventions to promote collaboration awareness. *Computer Supported Cooperative Work (CSCW),* Vol. 18, 301-330. https://doi.org/10.1007/s10606-009-9093-z

[15] Federico Cabitza, Marcello Sarini, and Carla Simone. 2007. Providing awareness through situated process maps: the hospital care case. In *Proceedings of the 2007 ACM International Conference on Supporting Group Work (GROUP '07).* Association for Computing Machinery, New York, NY, USA, 41–50. https://doi.org/10.1145/1316624.1316631

[16] Carrie J. Cai, Emily Reif, Narayan Hegde, Jason Hipp, Been Kim, Daniel Smilkov, Martin Wattenberg, Fernanda Viegas, Greg S. Corrado, Martin C. Stumpe, and Michael Terry. 2019. Human-centered tools for coping with imperfect algorithms during medical decision-making. *In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19).* Association for Computing Machinery, New York, NY, USA, Paper 4, 1–14. https://doi.org/10.1145/3290605.3300234

[17] Francisco Maria Calisto, Nuno Nunes, and Jacinto C. Nascimento. 2020. BreastScreening: On the use of multi-modality in medical imaging diagnosis. In *Proceedings of the International Conference on Advanced Visual Interfaces (AVI '20).* Association for Computing Machinery, New York, NY, USA, Article 49, 1–5. https://doi.org/10.1145/3399715.3399744

[18] Francisco Maria Calisto, Carlos Santiago, Nuno Nunes, Jacinto C. 2021. Introduction of human-centric AI assistant to aid radiologists for multimodal breast image classification. *International Journal of Human-Computer Studies*, Vol. 150, 102607. https://doi.org/10.1016/j.ijhcs.2021.102607

[19] Francisco Maria Calisto, Carlos Santiago, Nuno Nunes, Jacinto C. 2022. BreastScreening-AI: Evaluating medical intelligent agents for human-AI interactions. *Artificial Intelligence Medicine*, Vol. 127, 102285. https://doi.org/10.1016/j.artmed.2022.102285

[20] John M. Carroll, Mary Beth Rosson, Gregorio Convertino, and Craig H. Ganoe. 2006. Awareness and teamwork in computer-supported collaborations. *Interacting with Computers* Vol. 18, 1, 21–46. http://dx.doi.org/10.1016/j.intcom.2005.05.005

[21] Christian Castaneda, Kip Nalley, Ciaran Mannion, Pritish Bhattacharyya, Patrick Blake, Andrew Pecora, Andre Goy, and K Stephen Suh. 2015. Clinical decision support systems for improving diagnostic accuracy and achieving precision medicine. *Journal of Clinical Bioinformatics*, Vol. 5, 1, 1–16. https://doi.org/10.1186/s13336-015-0019-3

[22] John R. Clarke, Stanley Z. Trooskin, Prashant J. Doshi, Lloyd Greenwald, and Charles J. Mode. 2002. Time to laparotomy for intra-abdominal bleeding from trauma does affect survival for delays up to 90 minutes. *The Journal of Trauma: Injury, Infection, and Critical Care* Vol. 52, 3, 420–425. http://dx.doi.org/10.1097/00005373-200203000-00002

[23] Jacques Cohen. 1996. Special Issue: Digital Libraries. *Communications of the ACM, Vol.* 39, 11 (November 1996).

[24] Kadian Davis, Evans Owusu, Jun Hu, Lucio Marcenaro, Carlo Regazzoni, and Loe Feijs. 2016. Promoting social connectedness through human activity-based ambient displays. In *Proceedings of the International Symposium on Interactive Technology and Ageing Populations (ITAP '16).* Association for Computing Machinery, New York, NY, USA, 64–76. https://doi.org/10.1145/2996267.2996274

[25] Nicholas P Dempsey. Simulated recall interviews in ethnography. *Qualitative Sociology* Vol. 33, 349-367 (2010). https://doi.org/10.1007/s11133-010-9157-x

[26] R. Key Dismukes, Janeen A. Kochan, and Timothy E. Goldsmith. 2018. Flight crew errors in challenging and stressful situations. *Aviation Psychology and Applied Human Factors*, Vol. 8, 1, 35–46. https://doi.org/10.1027/2192-0923/a000129

[27] David Drummond, et al. 2016. An innovative pedagogic course combining video and simulation to teach medical students about pediatric cardiopulmonary arrest: a prospective controlled study. *European Journal of Pediatrics*, Vol. 175, 6, 767-74. https://doi.org/10.1007/s00431-016-2702-1

[28] Lesley Curtis, Ewoud Ter Avest, Joanne Griggs, Richard Lyon. (2020). The ticking clock: does actively making an enhanced care team aware of the passage of time improve pre-hospital scene time following traumatic incidents? *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine.* Vol. 28, 1, 1-8. https://doi.org/10.1186/s13049-020-00726-9

[29] Bruce P. Douglass. 1998. Statecarts in use: structured analysis and object-orientation. *In Lectures on Embedded Systems, Grzegorz Rozenberg and Frits W. Vaandrager (Eds.). Lecture Notes in Computer Science*, Vol. 1494, 368–394. http://dx.doi.org/10.1145/3-540-65193-429

[30] Marc A Ellsworth, et al. 2017. An appraisal of published usability evaluations of electronic health records via systematic review. *Journal of the American Medical Informatics Association: JAMIA* Vol. 24, 1 (2017), 218-226. https://doi.org/10.1093/jamia/ocw046

[31] Mica Endsley. 1995. Toward a theory of situation awareness in dynamic systems." *Human Factors*, Vol. 37, 1, 32–64. https://doi-org/10.1518/001872095779049543

[32] Sofia Erestam, et al. A survey of surgeons' perception and awareness of intraoperative time utilization. *Patient Safety in Surgery* Vol. 8, 30, 1-6. https://doi.org/10.1186/1754-9493-8-30

[33] You Fang, Yan Xu, Jun Zhang, and Wei Cui. 2022. Design factors of shared situation awareness interface in human–machine co-driving. *Information* Vol. 13, 9, 437-454. https://doi.org/10.3390/info13090437

[34] Ben Green, David Parry, and Rachel Oeppen. 2016. Situational awareness - what it means for clinicians, its recognition and importance in patient safety. *Oral Diseases* Vol. 23, 6, 721–725. http://dx.doi.org/10.1111/odi.12547

[35] Paul R. Greig, Danaja Zolger, Desire N. Onwochei, Neal Thurley, Helen Higham, and Neel Desai. 2022. Cognitive aids in the management of clinical emergencies: A systematic review. *Anaesthesia* (First published 14 December 2022). http://dx.doi.org/10.1111/anae.15939

[36] Vincent Grosjean and Patrice Terrier. 1999. Temporal awareness: pivotal in performance? *Ergonomics*, Vol. 42, 11, 1443-1456, https://doi.org/10.1080/001401399184802

[37] Gregory Gruen, et al. 2006. Patterns of errors contributing to trauma mortality. *Annals of Surgery* Vol. 244, 3, 371–80. https://doi.org/10.1097/01.sla.0000234655.83517.56

[38] Miguel Cabral Guerra, Deedee Kommers, Saskia Bakker, Pengcheng An, Carola van Pul, and Peter Andriessen. 2019. Beepless. *Proceedings of the 2019 on Designing Interactive Systems Conference* (*DIS '19).* http://dx.doi.org/10.1145/3322276.3323696

[39] Carl Gutwin, et al. 2002. A descriptive framework of workspace awareness for real-time groupware. *Computer Supported Cooperative Work*, Vol. 11, 3-4, 411-446. https://dl.eusset.eu/handle/20.500.12015/3612

[40] Christian Heath, Marcus Sanchez Svensson, Jon Hindmarsh, Paul Luff, and Dirk Vom Lehn. 2002. Configuring awareness. *Computer Supported Cooperative Work (CSCW)* Vol. 11, 3, 317–347. https://doi.org/10.1023/A:1021247413718

[41] Sarah E. Henrickson Parker, Aaron A. Laviana, Rishi K. Wadhera, Douglas A. Wiegmann, and Thoralf M. Sundt. 2010. Development and evaluation of an observational tool for assessing surgical flow disruptions and their impact on surgical performance. *World Journal of Surgery* 34, 2, 353-361. http://dx.doi.org/10.1007/s00268-009-0312-z

[42] Stephen G Henry and Michael G Fetters. 2012. Video elicitation interviews: a qualitative research method for investigating physician-patient interactions. *Annals of Family Medicine*, vol. 10, 2, 118-25. https://doi.org/10.1370/afm.1339

[43] Richard J. Holden, Pascale Carayon, Ayse P. Gurses, Peter Hoonakker, Ann Schoofs Hundt, A. Ant Ozok and A. Joy Rivera-Rodriguez. 2013. SEIPS 2.0: a human factors framework for studying and improving the work of healthcare professionals and patients. *Ergonomics*, Vol. 56. 11, 1669-1686. https://doil/org/10.1080/00140139.2013.838643

[44] Yue-Yung Hu, Alexander F. Arriaga, Emilie M. Roth, Sarah E. Peyre, Katherine A. Corso, Richard S. Swanson, Robert T. Osteen et al. 2012. Protecting patients from an unsafe system: the etiology & recovery of intra-operative deviations in care. *Annals of Surgery,* Vol. 256, 2, 203. https://doi.org/10.1097/SLA.0b013e3182602564

[45] Patrick G Hughes, Rami A Ahemd. 2019. Blindfolded trauma team resuscitation: A strategy for improved leadership and communication. *BMJ Simulation & Technology Enhanced Learning*, Vol. 9, 3, 174-175. https://doi.org/10.1136/bmjstel-2017-000277

[46] Jennifer Jewer et al. 2019. Evaluation of a mobile telesimulation unit to train rural and remote practitioners on high-acuity low-occurrence procedures: Pilot randomized controlled trial. *Journal of Medical Internet Research*, Vol. 21, 8, e14587. https://doi.org/10.2196/14587

[47] Brennan Jones, Anthony Tang, and Carman Neustaedter. 2020. Remote communication in wilderness search and rescue. *Proceedings of the ACM on Human-Computer Interaction* Vol. 4, GROUP (2020), 1–26. http://dx.doi.org/10.1145/3375190

[48] Gregory J. Jurkovich, Diane Campbell, Herry Padtra, and Arnole Luterman. 1987. Paramedic perception of elapsed field time. *The Journal of Trauma: Injury, Infection, and Critical Care* Vol. 27, 8, 892–897. http://dx.doi.org/10.1097/00005373-198708000-00008

[49] Tom Kontogiannis and Stathis Malakis. 2013. Strategies in coping with complexity: Development of a behavioural marker system for air traffic controllers. *Safety Science* Vol. 57, 27–34. http://dx.doi.org/10.1016/j.ssci.2013.01.014

[50] Kali M. Kuhlenschmidt, Elias Choi, et al. 2022. Provider perception of time during trauma resuscitation: A Prospective quantitative trauma video review analysis. *The Journal of Surgical Research,* Vol. 274, 207-212. https://doi.org/10.1016/j.jss.2021.12.048

[51] Diana S. Kusunoki, Aleksandra Sarcevic, Zhan Zhang, and Maria Yala. 2015. Sketching awareness: A participatory study to elicit designs for supporting ad hoc emergency medical teamwork. *Computer Supported Cooperative Work (CSCW)* Vol. 24, 1, 1–38. https://doi.org/10.1007/s10606-014-9210-5

[52] Diana S. Kusunoki and Aleksandra Sarcevic. 2015. Designing for temporal awareness. *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW '15).* http://dx.doi.org/10.1145/2675133.2675279

[53] Katherine E. Law, Emily A. Hildebrand, Hunter J. Hawthorne, M. Susan Hallbeck, Russell J. Branaghan, Sean C. Dowdy, and Renaldo C. Blocker. 2019. A pilot study of non-routine events in gynecological surgery: Type, impact, and effect. *Gynecologic Oncology* Vol. 152, 2, 298-303. https://doi.org/10.1016/j.ygyno.2018.11.035

[54] Alice C. Li et al. 2012. Integrating usability testing and think-aloud protocol analysis with "near-live" clinical simulations in evaluating clinical decision support. *International Journal of Medical Informatics*, Vol. 81,11, 761-72. https://doi.org/10.1016/j.ijmedinf.2012.02.009

[55] Junfeng Liao, Xu Chen, and Qi Zhang. 2018. Research on virtual personality of role playing online game users. *Proceedings of the 4th International Conference on Virtual Reality Association for Computing Machinery (ICVR'18)*, 10–14. https://doi.org/10.1145/3198910.3198913

[56] Lennart Lovstrand. 1991. Being selectively aware with the Khronika system. *Proceedings of the Second European Conference on Computer Supported Cooperative Work (ECSCW'91)*, 265–277. http://dx.doi.org/10.1007/978-94-011-3506-1_20

[57] Paul Luff, Christian Heath, and Marcus Sanchez Svensson. 2008. Discriminating conduct: Deploying systems to support awareness in organizations. *International Journal of Human-Computer Interaction*, Vol. 24, 4, 410–436. https://doi.org/10.1080/10447310801920490

[58] Andrii Matviienko, Maria Rauschenberger, Vanessa Cobus, Janko Timmermann, Jutta Fortmann, Andreas Löcken, Heiko Müller, Christoph Trappe, Wilko Heuten, and Susanne Boll. 2015. Towards new ambient light systems: a close look at existing encodings of ambient light systems. *Interaction Design and Architecture(s) Journal*, Vol. 26, 10-24.

[59] Nicolette McGeorge, Sudeep Hegde, Rebecca L. Berg, Theresa K. Guarrera-Schick, David T. LaVergne, Sabrina N. Casucci, A. Zachary Hettinger, et al. 2015. Assessment of innovative emergency department information displays in a clinical simulation center. *Journal of Cognitive Engineering and Decision Making* Vol. 9, 4, 329–46. https://doi.org/10.1177/1555343415613723

[60] National Center for Health Statistics. 2020. *Leading Causes of Death.* National Vital Statistics System. CDC

[61] Sara Montagna et al. 2020. Complementing agents with cognitive services: A case study in healthcare. *Journal of Medical Systems*, Vol. 44, 10, 1-10. https://doi.org/10.1007/s10916-020-01621-7

[62] Annette Moxey, Jane Robertson, David Newby, Isla Hains, Margaret Williamson, and Sallie-Anne Pearson. 2010. Computerized clinical decision support for prescribing: provision does not guarantee uptake. *Journal of the American Medical Informatics Association*, Vol. 17, 1, 25–33. https://doi.org/10.1197/jamia.M3170

[63] Roderick Murray-Smith, Antti Oulasvirta, Andrew Howes, Jörg Müller, Aleksi Ikkala, Miroslav Bachinski, Arthur Fleig, Florian Fischer, and Markus Klar. 2022. What simulation can do for HCI research. *Interactions*, Vol. 29, 6, 48–53. https://doi.org/10.1145/3564038

[64] Siegfried Müller, Raji Ghawi, and Jürgen Pfeffer. 2021. Using communication networks to predict team performance in massively multiplayer online games. *Proceedings of the 12th IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM '20)*, 353–360. https://doi.org/10.1109/ASONAM49781.2020.9381481

[65] Thanh Nguyen, Chee Peng Lim, Ngoc Duy Nguyen, Lee Gordon-Brown, and Saeid Nahavandi. 2019. A review of situation awareness assessment approaches in aviation environments. *IEEE Systems Journal* Vol. 13, 3, 3590–3603. http://dx.doi.org/10.1109/jsyst.2019.2918283

[66] Cliodhna O'Connor, and Helene Joffe. Intercoder reliability in qualitative research: Debates and practical guidelines, *International Journal of Qualitative Methods,* (2020). https://doi.org/10.1177/1609406919899220

[67] JaeYeon Park et al. 2021. Disentangling the clinical data chaos: User-centered interface system design for trauma centers. *PLoS ONE*, Vol. 16, 5, e0251140. https://doi.org/10.1371/journal.pone.0251140

[68] Avi Parush, et al. 2017. Can a technological cognitive aid improve teamwork and situational awareness (SA) in ED resuscitation? Design and a pilot study of a team situation display. *Journal of Biomedical Informatics* Vol. 76, 154–161. https://doi.org/10.1016/j.jbi.2017.10.009

[69] Nolan B. Petrosoniak, et al. 2021. Defining adverse events during trauma resuscitation: a modified RAND Delphi study. *Trauma Surgery Acute Care Open.* Vol. 19, 6, e000805. https://doi.org/10.1136/tsaco-2021-000805

[70] Carla M. Pugh, Susan Santacaterina, Debra A DaRosa, and Richard E. Clark. 2011. Intra-operative decision making: More than meets the eye. *Journal of Biomedical Informatics.* Vol. 44, 3, 486-496. https://doil.org/10.1016/j.jbi.2010.01.001

[71] Madhu C. Reddy, Paul Dourish, and Wanda Pratt. Temporality in medical work: Time also matters. *Computer Supported Cooperative Work (CSCW)*, Vol. 15, 1, 29–53. https://doi.org/10.1007/s10606-005-9010-z

[72] Gordon Rugg and Peter McGeorge. 1997. The sorting techniques: a tutorial paper on card sorts, picture sorts and item sorts. *Expert Systems*, Vol. 14, 80-93. https://doi.org/10.1111/1468-0394.00045

[73] Safiya Richardson et al. 2017. "Think aloud" and "Near live" usability testing of two complex clinical decision support tools. *International Journal of Medical Informatics* Vol. 106, 1–8. http://dx.doi.org/10.1016/j.ijmedinf.2017.06.003

[74] Jason J Saleem, Emily S Patterson, Laura Militello, Steve N Asch, Braldey N Doebbeling, and Marta L Render. Using human factors methods to design a new interface for an electronic medical record. *AMIA Annual Symposium Proceedings (AMIA '07)*, 640-644.

[75] Kjeld Schmidt and Liam Bannon. 1992. Taking CSCW seriously. *Computer Supported Cooperative Work* (*CSCW)* Vol. 1, 1-2, 7–40. http://dx.doi.org/10.1007/bf00752449

[76] Lee Soyoung, Tang Charlotte, Park Sun Young, Chen Yunan. 2012. Loosely formed patient care teams: Communication challenges and technology design. *Proceedings of the Conference on Computer-Supported Cooperative Work (CSCW'12)*, 867-876.

[77] Wei Shao, Arian Prabowo, Sichen Zhao, Siyu Tan, Piotr Koniusz, Jeffrey Chan, Xinhong Hei, Bradley Feest, and Flora D. Salim. 2019. Flight delay prediction using airport situational awareness map. *Proceedings of the 27th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (SIGSPATIAL '19)*, 432–435. https://doi.org/10.1145/3347146.3359079

[78] Mark Stefik, Gregg Foster, Daniel G. Bobrow, Kenneth Kahn, Stan Lanning, and Lucy Suchman. 1987. Beyond the chalkboard: computer support for collaboration and problem solving in meetings. *Communications of the ACM*, Vol.1, 32–47. http://doi.org/10.1145/7885.7887

[79] Karel Vredenburg, Ji-Ye Mao, Paul W. Smith, and Tom Carey. 2002. A survey of user-centered design practice. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02*), 471–478. https://doi.org/10.1145/503376.503460

[80] Torben Wallbaum, Maria Rauschenberger, Janko Timmermann, Wilko Heuten, and Susanne Boll. 2018. Exploring social awareness. *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems.* http://dx.doi.org/10.1145/3170427.3174365

[81] Rachel B Webman, et al. 2016. Classification and team response to nonroutine events occurring during pediatric trauma resuscitation. *The Journal of Trauma and Acute Care Surgery,* Vol. 81, 4, 666-73. https://doi.org/10.1097/TA.0000000000001196

[82] Priscilla West, et al. 2012. Improving patient safety and optimizing nursing teamwork using crew resource management techniques. *The Journal of Nursing Administration*, Vol. 42, 1, 15-20. https://doi.org/10.1097/NNA.0b013e31823c17c7

[83] Anping Xie and Carayon Pascale. 2015. A systematic review of human factors and ergonomics (HFE)-based healthcare system redesign for quality of care and patient safety. *Ergonomics*, Vol. 58, 1, 33-49. https://doi.org/10.1080/00140139.2014.959070

[84] Xiao Yan, Stephen Schenkel, Samer Faraj, Colin F. MacKenzie, and Jacqueline Moss. 2007. What whiteboards in a trauma center operating suite can teach us about emergency department communication. *Annals of Emergency Medicine*, Vol. 50, 4, 387–395. https://doi.org/10.1016/j.annemergmed.2007.03.027

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