Informing Digital Cognitive Aids Design for Emergency Medical Work by Understanding Paper Checklist Use

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ABSTRACT
We examine the use of a paper-based checklist during 48 simulated trauma resuscitations to inform the design of digital cognitive aids for safety-critical medical teamwork. Our analysis focused on team communication and interaction behaviors as physician leaders led resuscitations and administered the checklist. We found that the checklist increased the amount of communication between the leader and the team, but did not compromise the leader's interactions with the environment. In addition, we observed several changes in team dynamics: the checklist facilitated collaborative decision making and process reflections, but it also made some team members reactive rather than proactive. As the push toward digitizing medical work continues, we expect that paper checklists will soon be replaced by their digital counterparts. Designing interactive cognitive aids for medical domains, however, poses many challenges. Our results offer directions for how these tools could be designed to support medical work in increasingly digital environments.

Categories and Subject Descriptors
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Keywords
Medical checklist; Digital cognitive aids; Communication; Team dynamics; Leadership; Emergency medicine.

1. INTRODUCTION
Medical checklists are considered valuable tools in preventing and managing errors, reducing risks, and improving patient outcomes [12]. They have become increasingly common in healthcare and are now used across different medical settings, including anesthesia [13], operating rooms (OR) [16], and intensive care units (ICU) [18]. Most medical checklists, however, are paper-based, requiring care providers to manually record the presence or absence of the checklist items. Given the intrinsic qualities of paper and values it brings to the clinical environment—as shown by seminal work in HCI and CSCW [1],[9],[14]—this persistence of paper-based aids is not surprising. Even so, current approaches for recording clinical information are time-consuming and yield data of variable accuracy [6]. Developing more accurate medical records and more effective documentation methods are essential aspects of modernizing and improving our healthcare system.

The information captured in medical records is important for clinical decision making, care coordination, and as a source of research data, yet these functions are limited by current systems that use handwritten records or rely on manual entry into electronic health records (EHRs). Attempts to digitize paper records in trauma resuscitation began two decades ago [11] and have only recently been implemented at a few trauma centers, including Nationwide Children's Hospital [24] and the Hospital of the University of Pennsylvania [personal communication]. We believe this trend toward digitization of emergency medical care will continue, offering a range of benefits: better integration with EHRs used in other hospital units, improved data collection for quality improvement, real-time feedback on activities (e.g., alerts for skipped tasks), improved efficiency, and data display for entire teams rather than just for those who document patient encounters. Likewise, with the digitization of medical work proceeding fast, paper checklists may soon be replaced by interactive digital tools. In fact, efforts to design and develop digital checklists during crisis situations are already underway [22],[23]. Emergency medical domains, however, pose many challenges to designing interactive cognitive aids. Checklist design principles taken from the aviation industry have worked well for static, paper-based checklists [10], but may not be applicable to designing digital checklists for the dynamic and, often more chaotic, medical work. Moreover, checklist evaluation studies have mostly focused on assessing compliance and correct completion rates, with little data published on how checklist administration affects communication and interaction among members of a medical team [12],[16].

In this paper, we examine the effects of a paper-based checklist introduced to prepare for patient arrival and for use throughout patient evaluation in a trauma center of a major urban, pediatric teaching hospital. We began our inquiry by asking: How does checklist administration affect the functions of the checklist administrator—physician leader? How does it affect the leader's communication and interaction with the team? How does it affect team dynamics? Our results show how the checklist increased the amount of communication between the leader and the team, while also facilitating process reflections and joint decision making. We also show how the affordances of the checklist supported various leadership functions, led to good communication redundancy, and reinforced on-the-job training for less experienced team members. The study suggests that the practices that emerged as a result of the checklist use are important to sustain and should be considered in the design of interactive cognitive aids.

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Pre-arrival Plan

Check or prepare:
- ☐ Oxygen
- ☐ Suction
- ☐ Bag and mask
- ☐ Intubation tray
- ☐ Intubation medications
- ☐ Defibrillator
- ☐ CPR board

☐ Consider ordering blood

Assign team roles:
- ☐ Airway
- ☐ IV/IO access
- ☐ Primary survey
- ☐ Team leadership

☐ Brief team on incoming patient

☐ Estimate weight: _____ kg

Primary Survey

A	☐ Confirm C-spine is immobilized ☐ Confirm airway is protected
B	☐ Place O_2 mask or connect existing mask to O_2
C	☐ Check pulses ☐ Establish IV/IO access ☐ Consider ordering blood
D	☐ State GCS (eyes, verbal, motor) ☐ State pupil size and response
E	☐ Completely remove patient's clothing ☐ Cover patient with warm blanket
RE-EVALUATE AIRWAY	☐ Evaluate need for intubation ☐ Report ET tube size and depth (if applicable) ☐ Confirm $ETCO_2$ color change (if applicable)
MONITOR	☐ Confirm heart rate is displayed ☐ Confirm pulse ox waveform is displayed
VITALS	State and evaluate whether WNL: ☐ Heart rate ☐ Respiratory rate ☐ Blood pressure ☐ Oxygen saturation ☐ Temperature

Secondary Survey

Evaluate and state findings:
- ☐ Head
- ☐ Ears
- ☐ Eyes
- ☐ Facial bones
- ☐ Nose
- ☐ Mouth
- ☐ Neck/C-spine
- ☐ Chest
- ☐ Abdomen
- ☐ Pelvis
- ☐ Upper extremities
- ☐ Lower extremities
- ☐ Log roll and back exam

Plan of Care

Determine need for:

Laboratory tests	☐ Yes	☐ No
X-rays	☐ Yes	☐ No
CT scans	☐ Yes	☐ No
OR notification	☐ Yes	☐ No
PICU notification	☐ Yes	☐ No

Departure Plan

☐ State patient destination

Prepare patient for travel:
- ☐ Equipment
- ☐ Medications
- ☐ Identify who will travel with patient

Figure 1: Trauma resuscitation checklist used in the checklist evaluation study at our research site.

We make three contributions in this work. First, we provide a detailed exploration of how the paper checklist affected leadership functions and team dynamics during emergency medical events. Second, we describe the practices that emerged as a result of the checklist use. Third, we offer design directions to support these practices as medical work becomes increasingly digital.

2. BACKGROUND & RESEARCH CONTEXT

2.1 Trauma Resuscitation Domain Overview

Trauma resuscitation is a complex, high-tempo process that requires well-coordinated effort of all team members to ensure timely patient care. The primary goal is to stabilize a critically injured patient in a short time period by identifying injuries and developing a plan for patient hospitalization. This goal is typically achieved through three stages: (1) preparation for the patient arrival (pre-arrival stage), (2) primary and secondary survey (patient evaluation stage), and (3) plan of care (departure stage).

The pre-arrival stage begins with a pager notification of an incoming trauma patient. Upon being notified, members of the trauma team rapidly gather in the resuscitation bay, a designated room in the emergency department for performing resuscitations. Teams usually have between five to 20 minutes to carry out preparatory activities and learn about the incoming patient.

Shortly after patient arrival, the team proceeds with patient evaluation following the Advanced Trauma Life Support [ATLS] protocol. The first phase (*primary survey*) is a rapid evaluation of major physiological systems, consisting of five steps ("ABCDEs"): (1) airway [**A**], (2) breathing [**B**], (3) circulation [**C**], (4) neurological status [**D**], and (5) exposure and environmental control [**E**]. These steps are then followed by a detailed head-to-toe evaluation (*secondary survey*) and diagnostic tests (e.g., x-ray examinations) to identify other injuries.

The departure stage and plans for definitive care begin after the patient has been stabilized. During this stage, the surgical team leader and emergency medicine physician work together to determine the next step in the care process.

2.2 Resuscitation Teams & the Role of the Physician Leader

The size of a resuscitation team ranges from seven to 15 providers, depending on the type and severity of injury. The team typically consists of a physician leader, an emergency medicine physician, a physician surveyor, an anesthesiologist, a respiratory therapist, bedside nurses, and a scribe nurse. Because of the *ad hoc* nature of their work, team members may not necessarily know each other. Resuscitation teams are hierarchical, with each team member having a defined role and a set of responsibilities. For example, a physician surveyor (junior surgical resident) performs hands-on patient evaluation and calls out the findings to the leader. Bedside nurses take blood pressure measurements and establish intravenous (IV) access, while the scribe documents the resuscitation process on a paper flowsheet.

The role of the physician leader is critical in ensuring that each phase of care flows in continuity. This role is usually assigned to an attending surgeon, a surgical fellow, or a senior surgical resident. The leader is responsible for supervising patient care, delegating tasks, and making decisions while being positioned at the foot of the bed for a quick overview of the patient, team and resuscitation room. Because leaders mostly rely on the findings reported by the physician surveyor, they are generally hands-off when it comes to patient evaluation. Sometimes, however, a lack of expertise in the room may require the leaders to assist with bedside tasks. Because the role of the leader is critical, it is important to understand how cognitive aids, whether paper or digital, impact the leadership functions and team dynamics.

2.3 An Opportunity for Study: Trauma Resuscitation Checklist

Despite the hierarchical nature of trauma teams, compliance with essential components of the ATLS protocol is variable, even among experienced providers and teams [7]. The performance improvement and research staff at our site have similarly observed variable compliance with the recommended steps of the protocol using video review of actual resuscitations [3]. To help teams reduce errors and delays in treatments, the Chief of Trauma introduced a checklist, the first of its kind in this medical domain (Figure 1). The checklist was designed for team leaders and was meant to serve as a compliance tool. The pre-arrival section contained items that helped teams prepare for patient arrival. The primary and secondary survey sections followed the protocol steps, including the ABCDEs, head-to-toe evaluation, and vital signs checking. The plan of care and departure items facilitated discussions about the diagnostic tests and patient disposition.

Before it was officially implemented, the checklist went through an iterative design process. Its impact on team performance was then evaluated in a simulated environment with 12 unique trauma teams participating in 12 experimental sessions representing three conditions: control, the do-list checklist scenario, and the challenge-response checklist scenario [17]. Two checklist administration methods were evaluated: a *do-list* method and a *challenge-response* method. The do-list method required the leader to call out each item and await verbal confirmation of task completion before moving onto the next item. In contrast, the challenge-response method required the leader to call for a pause at various times during the resuscitation, read aloud each item, and then wait for a team member to verbally confirm task completion. Checklist administration was assigned to the physician leader, a role least likely to be hands-on during patient evaluation. Evaluation findings showed increased team performance during scenarios using a checklist and high overall compliance with the checklist in the experimental scenarios [17].

In this paper, we use the video recordings from the checklist evaluation study [17] to understand the impact of different paper-based checklist administration methods on team dynamics and work practices in an intense medical collaboration setting. Studying the use of paper artifacts in work processes as a way of directing or inspiring the design of new technologies is a common approach in HCI and CSCW [19]. Several studies specific to healthcare have also used this approach to inform the design of EHRs and other systems [4],[25]. Similarly, the use of a paper checklist in simulated resuscitations at our research site afforded an ecologically valid and controlled environment (control and two experimental checklist conditions) for understanding checklist effects on leadership and team behaviors, as well as for deriving design requirements for interactive cognitive aids.

Trauma resuscitation differs from other medical domains in which checklists have been used or tested, providing a rich site for studying the use of this paper artifact. Most team members are performing time-critical tasks, which may prevent a pause for performing a checklist. While documentation in other clinical settings can immediately follow the patient encounter, emergency physicians and nurses often multitask and face frequent interruptions in workflow [5]. In addition, the checklist administrators—in our case, physician leaders—must actively use the checklist to ensure task completion, which may interfere with their performance. By analyzing the use of the checklist across different experimental sessions, we gained an understanding of how this artifact affected both leadership and team behaviors. The two checklist administration methods also offered insights into different checklist use styles, allowing us to broaden design implications for interactive cognitive aids in time-critical medical teamwork.

3. METHODS

3.1 Dataset: Simulated Resuscitations

Our dataset included video recordings of 48 simulated resuscitations originally performed in a pediatric trauma center in the U.S. mid-Atlantic region for the purposes of evaluating the impact of the checklist on protocol compliance. Twelve unique teams participated in a total of 12 experimental sessions, each consisting of four scenarios representing three conditions: control (two scenarios per session, no checklist), the do-list checklist scenario, and the challenge-response checklist scenario. The dataset, therefore, included 12 teams running 24 control, 12 do-list and 12 challenge-response scenarios. Presentation of the scenarios was random to reduce carry-over effects. The clinical scenarios varied by patient age, injury mechanism, and required treatments.

The simulations were performed in an actual trauma bay using high-fidelity patient mannequins with features ranging from simulated speech, a realistic airway, breath sounds, simulated ECG rhythms and capabilities of performing intravenous access. The teams were instructed to carry out each resuscitation scenario as they normally would in an actual event. Before the checklist scenarios, team leaders were first given a brief demonstration of the assigned checklist administration method and then asked to adhere to this method throughout the resuscitation.

Participants were recruited from a pool of physicians and nurses who normally participate in trauma resuscitations at the hospital. Each team had eight members, including a physician leader (emergency medicine physician or surgeon), a physician surveyor (junior surgical resident), an airway physician (anesthesiologist or critical care fellow), a respiratory therapist, two bedside nurses, a scribe nurse, and a medication nurse. Participation was tracked to ensure that each experimental session had a unique team.

Two video cameras captured each simulation, allowing us to observe a variety of team behaviors. One camera provided an overhead view and the other provided a side view of the trauma bay. The average length of controls was 13 min, ranging from 9 to 16 min; the average length of do-list scenarios was 15 min, ranging from 9 to 21 min; and the average length of challenge-response scenarios was 17 min, ranging from 11 to 22 min.

3.2 Coding Scheme Development

To identify leadership behaviors, we first developed a coding scheme. This scheme was then used during video review to mark the leaders' communication and interaction instances in 48 simulations for further analysis. One researcher reviewed six simulation videos: two do-list checklist scenarios, two challenge-response checklist scenarios, and two control scenarios. These simulations were selected after scanning the entire dataset to represent different leadership styles (active vs. passive) and team efficiencies (short vs. long resuscitations), and to include all four clinical scenarios, which differed in complexity. This mix of simulations allowed us to uncover a broad range of behaviors using an open coding technique. The initial list of behaviors (codes) was then discussed in a group session to determine which codes to keep, merge, or remove. After the list of codes was set, we created a data dictionary defining each code to standardize the coding process. Our final coding scheme contained a total of 21 codes, 13 of which represented verbal communication behaviors and 8 represented physical interaction behaviors. *Communication codes* included the following behaviors: initiate team introductions, recap pre-hospital information, assign tasks, request information, report information, acknowledge information, provide clarification, summarize process, state decision, discuss decision, brief on departure plan, plan care, and explain procedure. *Interaction codes* included behaviors such as looks at the monitor, looks at the flowsheet, looks at the checklist, writes on the checklist, checks off checklist items, evaluates patient, assists with bedside tasks, and turns to the scribe for information.

3.3 Video Review and Data Analysis

Video review was performed independently by three researchers and consisted of multiple steps. Each video was first transcribed by the first researcher to provide a linear list of the leader's behaviors. The first and second researcher then coded the transcripts, while also jotting down notes about team behaviors. Specifically, the first researcher reviewed and coded all 48 simulations, and the second researcher reviewed and coded about 30% of the videos (15 randomly selected simulations representing all scenarios). Communication and interaction codes were accompanied by the stage code (e.g., pre-arrival, primary and secondary surveys, departure plan) to identify when in the process certain behaviors occurred. We also recorded time stamps for each behavior so that we can visualize them on a timeline.

We used Cohen's Kappa coefficient to determine the inter-rater reliability by comparing the coders' scores on the 15 simulations involving 995 communication and 601 interaction instances. The resulting kappa values were analyzed using the kappa interpretation scale suggested by Landis and Koch [15]. The coders presented "Almost Perfect" agreement on the interaction codes (kappa value of 0.851), and "Substantial" agreement on the communication codes (kappa value of 0.771). Communication disagreements were mainly due to the interpretive differences attributed to 'request information' and 'assign task' codes.

To identify themes related to checklist effects on team dynamics, we asked the third researcher to review a subset of checklist scenarios (6 out of 24 randomly selected checklist sessions) and focus on team behaviors only. The notes obtained from all three researchers were discussed in a group session, compared, and then analyzed using an open coding technique by the first researcher.

Once the video review was completed, we visualized the frequency of the leaders' communication and interaction behaviors on a timeline for all 12 teams to analyze their relationship to the checklist use. Due to space limitations we show visualizations for only one team (Team 2, Figure 2). To create these visualizations, we first divided the entire resuscitation into 30-second time intervals, and then counted the instances of communication and interaction behaviors within each time interval. To further support our analysis of the checklist effects, we conducted a paired-samples t-test with 95% confidence level to compare communication and interaction behaviors among the 12 leaders for the checklist and non-checklist conditions. Finally, we created bar charts showing the frequency of leaders' activities across all 48 simulations (Figure 3).

4. FINDINGS

We report our findings in three parts. We first describe the checklist effects on leaders' verbal communication, followed by the checklist effects on leaders' interaction with the environment. We then present the checklist effects on team dynamics.

4.1 Checklist and Leaders' Communication

Leadership responsibilities are best reflected through the leader's communication with the team. For example, leaders would inquire about the patient status as they make decisions, assign tasks, or provide an overview of the process to maintain team awareness. To understand the extent to which the checklist affected these leadership tasks, we first examined the relationship between the checklist use and overall communication. We then took a closer look into different communication behaviors.

By comparing the ground truth (non-checklist) with the two checklist administration methods (do-list and challenge-response), we observed an increased amount of the leader's communication behaviors in the checklist scenarios (Figure 2); the checklist design by itself and the ways in which it was used simply made the leader communicate more frequently with the team. A closer look into the two checklist administration methods revealed that the frequency of the leader's communication and checklist use varied, with each checklist administration method shaping the nature of the leader's communication with the team. For example, the do-list method required the leader to call out each checklist item and then await verbal confirmation of task completion. This checklist use style made the leader's communication equally distributed throughout the resuscitation (Figure 2, middle chart). In contrast, the challenge-response method required the leader to call for a pause at various times during the resuscitation (usually at the end of each phase), read aloud each item, and then wait for a verbal confirmation. As a result, the leader's communication spiked towards the end of each phase, with less communication in between (Figure 2, top chart). In short, the checklist use aligned almost perfectly with leaders' communication, shaping not only team communication but also the dynamics of the resuscitation.

Among 13 communication behaviors we identified, three emerged as particularly affected by the checklist (Figure 3(a)): *request information*, *report information*, and *initiate team introductions*. We next describe each of these communication behaviors.

4.1.1 Request Information

Requests for information were the most frequent communication behaviors observed in both checklist and control scenarios, with a significant difference in the amount of requests between the two conditions, $t(11) = 8.791$, $p = 0.000$ (Figure 3(a)). This notable difference suggests that the checklist prompted leaders to request information more frequently.

In particular, our analysis showed that leaders who used the checklist inquired more frequently about three types of information: patient status (e.g., findings from patient evaluation), process status (e.g., performed procedures), and equipment and medication availability. The pattern in which this information was solicited, however, differed across conditions. For example, throughout control scenarios, patient evaluation proceeded in a standard way: physician surveyor initiated evaluation by assessing the patient's physiological systems one by one, reporting findings to the leader after each ABCD step, with the leader requesting information only if the findings raised any concerns. The pattern of information requests in challenge-response scenarios was similar to that of controls, except that requests intensified at the end of the primary and secondary surveys when the leader asked for any missing information:

> After ABCD steps were completed, the leader called for a pause and read through the primary survey items, requesting information from the physician surveyor, *"Did you check pulses? Did you state the GCS? Pupils?"* [Session 10, Challenge-response scenario]

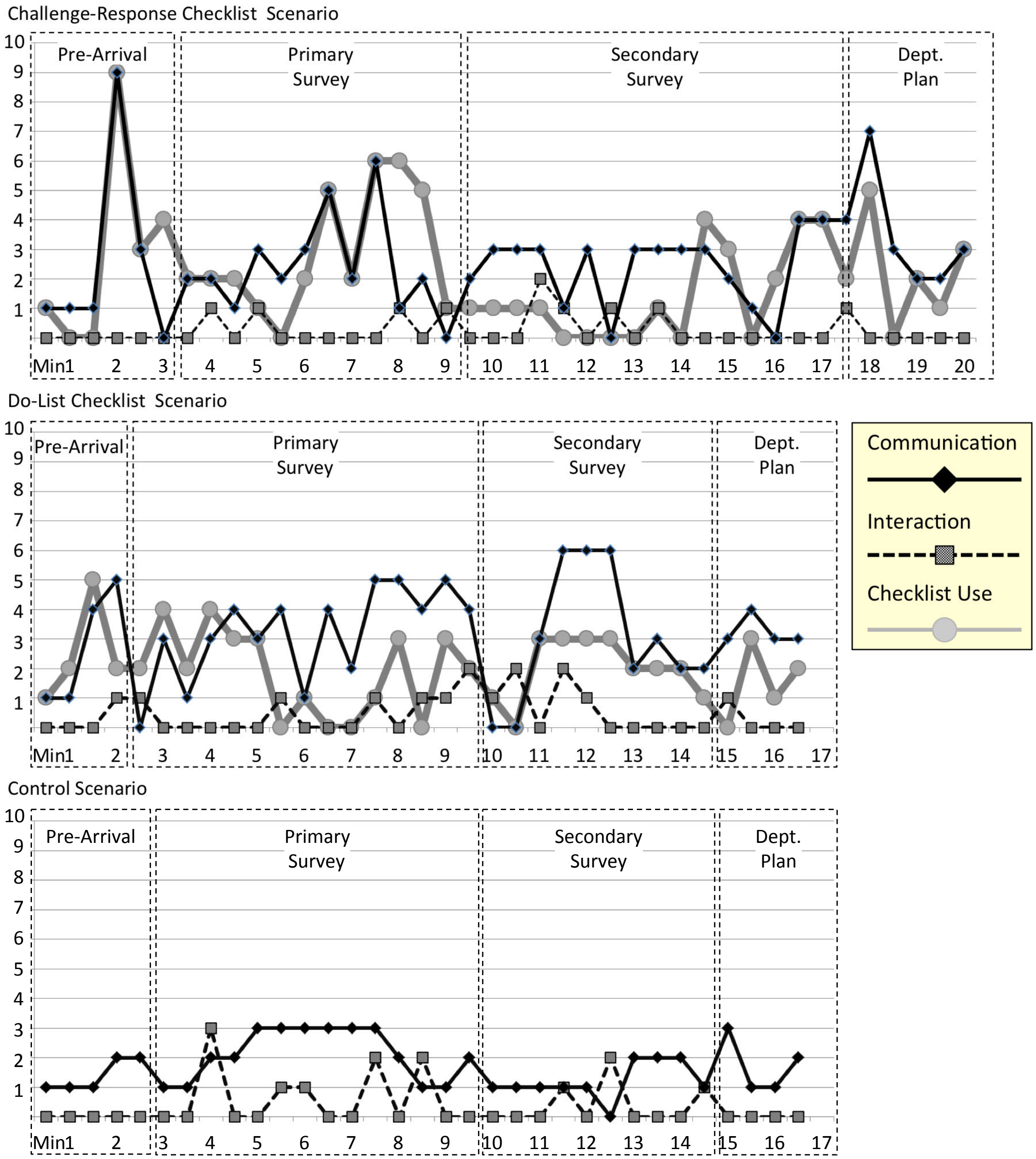

Figure 2: Relationships between the checklist use and the leader's communication and interaction behaviors, for Team 2, for three conditions (challenge-response scenario [top chart], do-list scenario [middle chart] and control scenario [bottom chart]).

In contrast, throughout the do-list scenarios, leaders requested information about findings from each evaluation step before physician surveyors started assessing the patient:

> Shortly after the patient was brought into the room, the leader looked toward the checklist and inquired, *"Protected airway?"* Hearing this prompt, the surveyor assessed the patient's airway and reported *"Yes."* [Session 6, Do-list scenario]

Requests for the overall status of the process, fluids, medications and other treatments occurred more frequently in checklist conditions, especially during the challenge-response scenarios when leaders actively used the checklist at the end of the resuscitation phases. In contrast, the use of the checklist in the do-list scenarios followed the process steps one by one, thereby increasing awareness of the overall process status.

Inquires about the equipment and other anticipated materials (e.g., blood products, medications) usually occurred during the pre-arrival stage. We observed, however, that leaders without the checklist rarely inquired about equipment or medications prior to patient arrival. In comparison, all 12 leaders inquired about equipment readiness before patient arrival in the do-list sessions, and 10 out of 12 leaders checked for equipment and other materials in the challenge-response sessions.

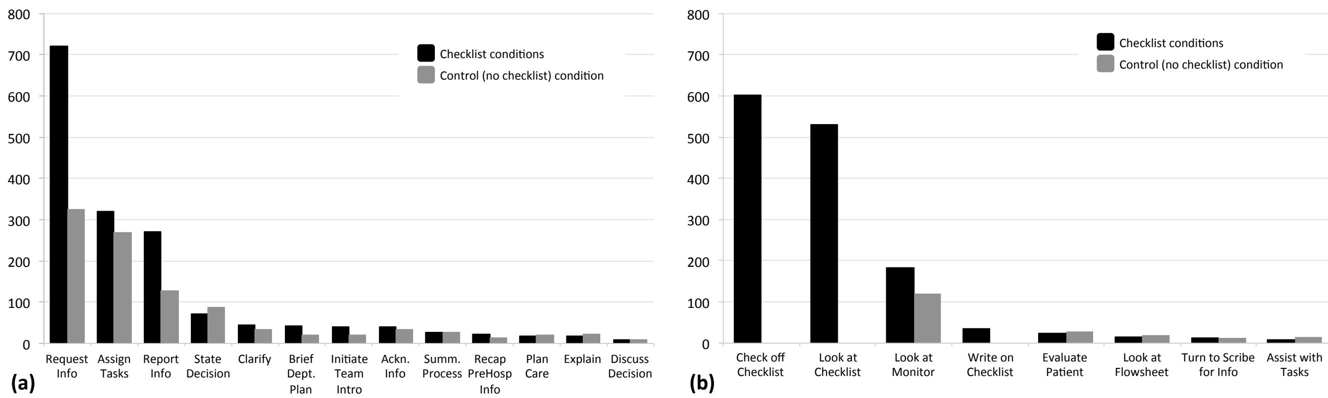

Figure 3: Aggregates of communication (a) and interaction (b) behaviors across 24 checklist (do-list and challenge-response) scenarios [black bars] and 24 control (no checklist) scenarios [gray bars].

4.1.2 Report Information

Over the course of the resuscitation, leaders would often report information back to the team about the patient or process status to help maintain overall team awareness. For example, they would restate major findings and go over current and future tasks. We found that the checklist significantly affected the leaders' reporting behavior—the amount of leaders' reports in the checklist sessions doubled compared to that of control sessions, $t(10) = 3.083$, $p = 0.012$ (Figure 3(a))—in that it prompted leaders to not only reevaluate and restate the patient's parameters and findings, but also provide their interpretations. We observed all 12 leaders frequently reporting task statuses and patient parameters in most checklist scenarios. For example:

> After the team successfully stabilized the patient's airway, the leader checked off the airway item on the checklist and reported, *"We have secured the airway so we go to the next part."* [Session 12, Do-list scenario]

> When the leader reached the "Vitals" section, he started looking at the vital signs monitor, reporting, *"Normal heart-rate, blood pressure is low right now, oxygen saturation is 100% and temperature is low."* [Session 4, Challenge-response scenario]

By comparison, the status of the process was reported in nine out of 24 controls and mostly referred to the current tasks (e.g., *"We have the patient intubated and everything is fine"* [Session 12]). Patient status was reported more frequently, with leaders stating vital signs and other patient data in 16 out of 24 control scenarios.

4.1.3 Initiate Team Introductions

Team introductions and role assignment during the pre-arrival stage were designed to introduce team members who did not know each other and to ensure that all team roles were covered. We found that the leaders initiated introductions in all but six simulations (five controls and one checklist). A major difference between the two conditions was that the leaders with checklists also confirmed responsibilities with particular roles, whereas leaders in controls rarely did so, $t(10) = 2.571$, $p = 0.028$. For example, in Session 2, the leader first asked other team members to introduce themselves by name. After the introductions, the leader called out each person by name and assigned roles:

> "*[Name] will be responsible for airway. [Name] will be responsible for IV access. [Name] for primary survey, and I will be the leader.*" [Session 2, Do-list scenario]

4.1.4 Other Communication Behaviors

Although no significant differences were found for other communication behaviors, we observed that the checklist played an important role during these activities. In particular, we found that *task assignments* increased only slightly in scenarios with the checklist (Figure 3(a)). We did observe, however, that leaders without the checklist failed to assign tasks during the pre-arrival and departure stages, whereas leaders in checklist scenarios regularly gave these orders. For example:

> While waiting for the patient, the leader went through the pre-arrival items and issued the following orders: *"Let's make sure everything is ready… oxygen is ready, med[ication]s are ready, suction is ready… 4.5 [tube size] for intubation… get IV and bag ready."* [Session 12, Challenge-response scenario]

The *plan of care* was discussed in only half of the simulations, while the *departure plan* was discussed in 21 out of 24 checklist scenarios and in 15 out of 24 non-checklist scenarios. The discussion of plans appeared more detailed with the checklist; it included laboratory orders, transfer medications, and the patient's next destination. Plan discussions in the control sessions mostly focused on laboratory orders. We also observed fewer *decisions stated* by the leaders in the checklist scenarios, though this difference was not significant. Finally, leaders in the checklist sessions regularly briefed their teams on incoming patients, providing quick summaries of pre-hospital information, or *pre-hospital recaps*. Though no significant difference was found between the two conditions, we observed fewer leaders in the controls performing this preparatory activity (10 out of 24).

4.2 Checklist and Leaders' Interactions

In addition to leading resuscitation teams through communicative acts such as task assignments, reports or process summaries, physician leaders exhibited their leadership through interactions with the patient and environment. Although hands-off most of the time (no direct involvement in patient physical examination), leaders would sometimes approach the patient to confirm reported findings or assess the patient's breathing or pulses. Leaders would also assist with some bedside tasks, such as help remove transfer boards or pass on equipment. Assigning the checklist to leaders meant keeping their hands and eyes busy with administering the checklist. We therefore examined whether checklists affected leaders' visual attention and interactions with the environment.

When looking into the distribution of interaction behaviors (e.g., looks at the monitor, evaluates patient), we found that regardless of the condition (non-checklist, do-list and challenge-response), leaders rarely assisted with bedside tasks (Figure 2). The checklist, however, did consume leaders' attention (Figure 3(b)). Between the two checklist conditions, leaders looked at the checklist about 600 times (on average, 18 times per challenge-response scenario and 26 times per do-list scenario). The duration of each look varied depending on the scenario and leadership style, and ranged from 1 second to more than 10 seconds. The do-list administration method resulted in a higher frequency of looks than the challenge-response method because it required the leader to look at the checklist before and after each task. On the other hand, the challenge-response method required the leader to look at the checklist during time-outs, when they called a pause to ensure task completions. Checking off items on the checklist added another few seconds (sometimes even minutes) to the overall time spent on the checklist. We observed shorter but more frequent check-offs during the do-list, as opposed to the challenge-response scenarios, when check-offs clustered around time-outs. We also observed that some leaders read through the items without checking them off, suggesting that differences in frequency and durations of the checklist use were driven not only by the method but also by individual preferences.

The checklist required the leaders to write down one piece of patient information—estimated weight. Occasionally, however, the leaders used the checklist to write down other patient information or take notes as other team members reported physical findings. Content analysis of handwritten notes from 24 checklists used in the study showed that eight leaders jotted down various pieces of pre-arrival information, such as demographics, estimated arrival time, mechanism of injury, and en-route treatments. A few leaders also recorded physical findings such as pulses, neurological status, size of pupils, temperature and vitals. The recorded information served as a memory aid, allowing for more efficient information retention, especially for rapidly changing values such as vital signs.

Although using the checklist consumed some of the leaders' time, we observed that the checklist did little to distract leaders from other tasks, especially those that required their visual attention. This observation was confirmed by statistical tests showing no significant differences between interaction behaviors in the checklist and control sessions (e.g., looks at monitor: $t(10) = 2.19$, $p = 0.051$; looks at flowsheet: $t(10) = -0.838$, $p = 0.420$). Even so, we observed that the checklist played an important role during these activities. In particular, the leaders looked at the vital signs monitor more often during the checklist sessions (183 times total) than control sessions (120 times total) (Figure 3(b)). On average, they looked at the monitor 5 times in the control scenarios, 6 times in the challenge-response scenarios, and 9 times in the do-list scenarios. (The checklist contained items requiring the leader to evaluate patient vitals after primary survey, as well as to check the monitor (Figure 1)). We also observed fewer instances of looking at the flowsheet in the checklist sessions (14 times total) than in the control sessions (20 times total) (Figure 3(b)). A possible explanation is that the checklist served as a memory aid—they used it to jot down notes, as described above—thus minimizing the need for flowsheet information.

The number of instances in which the leaders approached the bed or assisted with a task was low across all simulations, $t(10) = -0.461$, $p = 0.653$ (Figure 3(b)). We did, however, observe fewer approaches to the patient bed or assistances with tasks in the checklist sessions. Most of the time, leaders approached the patient only to take a closer look at an injury, without touching the patient. When they did engage with the patient, they either held the checklist in one hand and examined the patient with another, or they placed the checklist aside, as illustrated below:

> At about 6 minutes into the scenario, the leader asked the surveyor to prepare chest tube equipment, "*While you are preparing the chest tube, I will do the secondary survey.*" The leader then approached the bed, put the checklist aside and evaluated the patient. After completing the survey, the leader stepped back, picked up the checklist, returned to her position and checked off items on the secondary survey section. When she got to the "chest" item on the list, she again approached the patient and touched the patient's chest with one hand while holding the checklist in the other. [Session 3, Do-list scenario]

4.3 Checklist and Team Dynamics

In addition to observing checklist effects on leadership behaviors, we found that the checklist altered team dynamics in three ways: (1) it introduced changes in the communication and interaction patterns between the leader and other team members; (2) it helped facilitate collaborative information seeking and decision making; and, (3) it helped facilitate process summaries during which teams reflected on the overall process status.

4.3.1 Checklist Effects on Team Communication and Interaction: Reactive vs. Proactive Team Members

Our analysis of leaders' requests for information and responses they received across three conditions suggested that by adopting the checklist, some team members became "reactive" as opposed to being "proactive"—that is, they became dependent on the leader by waiting for the leader's prompts and questions. This effect was found in 25% of the checklist scenarios, most of which followed the do-list method. Furthermore, when observed, this behavior change occurred in almost every stage of the resuscitation. For example, airway physicians and bedside nurses relied on leaders' instructions to prepare equipment, medications, blood products and other supplies for patient arrival during the pre-arrival stage, as well as for patient transfer during the departure stage. During the primary and secondary surveys in particular, the checklist affected interaction between the leader and physician surveyor. By issuing prompts during patient evaluation—that is, requesting information about physical findings for each protocol step—the leader was guiding the surveyor step-by-step through the process rather than letting him or her perform evaluation and report findings on their own:

> The surveyor performed airway, breathing and circulation steps during the primary survey following the leader's prompts. When the leader paused to delegate tasks to other team members, (e.g., get a warm blanket, establish IV access), the physician surveyor stood still and waited for the order for the next step. Near the end of the primary survey, the leader looked at the checklist and then turned to the surveyor: "T*he primary survey is completed, except for pupil size and responses, please let me know when you get it.*" The surveyor then immediately started assessing the pupils. [Session 6, Do-list scenario]

Although the checklist altered interactions between the leader and physician surveyor, we believe these effects varied based on the surveyor's experience. We observed, for example, that in some events, even when the leader delegated specific tasks to the surveyor, the surveyor responded to those orders, but then continued evaluation on their own while the leader switched to other tasks. We also observed cases when physician surveyors worked independently and did not wait for the leader's guidance, even though the leaders tried hard to guide the process using the checklist. For example:

> Most of the team was still focused on the primary survey tasks, deciding what types of fluid and medications to administer, and whether or not to intubate the patient. Without receiving specific orders to move onto the secondary survey, the surveyor started with secondary tasks immediately after completing the initial survey. The surveyor first evaluated the right side of the patient. As he was about to move to the opposite side, the leader stopped him and asked to wait until the primary survey is completed. [Session 9, Do-list scenario]

These observations suggest that team members' experience levels play a critical role in shaping their interaction with the leader. Although we did not record work experience data, we believe that surveyors with more experience are more likely to perform patient evaluation on their own. Similarly, we believe that less experienced team members are more likely to benefit from the step-by-step guidance that the checklist afforded.

4.3.2 Checklist as a Trigger for Collaborative Information Seeking and Decision Making

Our analysis showed that the checklist increased the amount of communication between the leader and others in the team. As a result, the amount of team discussion and communication increased as well. Three findings stood out.

First, we observed team members mainly responding to assignments or requests that were relevant to their roles and responsibilities. For example, airway physicians usually responded to questions about the patient's airway; physician surveyors were primarily answering questions about primary and secondary survey; and, nurses responded to questions about intravenous access and medications. In other words, team members acquired, reported and memorized information about the domain in which they specialized. Reported information was then used for decision making; if more information was needed, the team went back to observation and data collection. This consistency in role-to-task relationship was observed in all 48 simulations. What stood out in checklist conditions, however, was an emphasis on group discussions when different roles engaged in clarifying ambiguous information, as illustrated below:

> The leader was considering blood administration for the patient, but was missing information such as weight, mechanism of injury, and administered fluids. Although some data were reported initially during patient handover, the leader did not record or remember this information. She asked physician surveyor, primary nurse, and airway physician to help her retrieve the needed information and decide on the blood volume. [Session 9, Do-list scenario]

> The leader was looking at the notes he jotted down on the checklist about the patient's pre-hospital information. He noticed a discrepancy between his notes and a finding that was previously reported by the surveyor. The leader then initiated a discussion with the surveyor in an attempt to clarify this finding. [Session 2, Challenge-response scenario]

These observations suggest that the checklist served not only as a tool for improving compliance with the protocol, but it also facilitated joint information seeking and team discussions. This practice was especially common in the pre-arrival and departure stages when leaders needed input from others on particular steps.

Second, we observed fewer solo decision-making instances in checklist conditions than in non-checklist conditions (Figure 3(a)). A possible explanation is that other team members, such as physician surveyors and airway physicians engaged in decision making by suggesting interventions:

> After checking off ABCDE steps, the leader paused at the next item, announcing, "*Evaluate need for intubation*." The leader first asked the surveyor and physician airway about their opinion. They then discussed whether or not to intubate the patient for a minute. The airway physician also suggested what medications were needed for intubation so that the nurse can prepare them. [Session 7, Challenge-response scenario]

Finally, we observed that the checklist, by facilitating team discussions and thus increasing the amount of communication, led to some redundant communication. Two kinds of communication redundancy were common. The first refers to repeating or acknowledging information after it is reported. A typical example we heard throughout simulations was "airway, check" uttered by the leader after the surveyor reported "airway is clear." As previous work has found, this communication redundancy is intended to confirm that the reported information has been heard and received by another person [2]. The second type of redundancy refers to the leader's inquires about the information that is already reported. Because the environment was often noisy and chaotic, leaders frequently missed reports by other team members, failing to record the information on their checklists; once they realized the information was missing, they asked for it.

4.3.3 Checklist as a Mechanism for Reflection: Process Summaries

The challenge-response checklist method—when the leader called for a pause at various times during the event and then went through the checklist—took more time to administer than the do-list checklist. At times, it took the leader up to two minutes to go over the checklist items, a pause that is often a luxury in an emergency situation. In addition, the entire team had to pause their activities for the checklist to be completed. Even so, we observed one positive change these pauses brought to the team—they offered an opportunity for the entire team (and not just the leader) to get a sense of where they stand in terms of completed, pending and remaining tasks, and reflect on the current status of the patient. Specifically, the long pauses occurring after each resuscitation phase during challenge-response scenarios allowed teams to review protocol steps, discuss findings and treatments, and decide on the next steps. Team members also used this opportunity to provide their own insights into the patient status and the plan of care. As such, the pauses helped bring the entire team on the same page, ensuring that no steps have been skipped and everyone was ready for the subsequent patient care steps.

5. DISCUSSION

Our analysis of leaders' communication and interaction behaviors during checklist scenarios confirmed the benefits of using a medical checklist found in other studies [12],[13],[16],[18]. The checklist, regardless of the administration method, prompted the leaders to regularly seek patient and process information, delegate tasks to other team members, confirm task completions, and maintain overall team awareness through brief reports. As such, the checklist helped improve compliance with the protocol, as found during the initial evaluation of its impact on team performance [17]. Our results also showed that the checklist did little to distract the leaders from paying attention to the vital signs monitor or hinder their engagement with the patient or environment when needed. Finally, we observed several practices at a team level that emerged as a result of the checklist use. The checklist facilitated collaborative decision making and process reflections, and led to good communication redundancy, but it also made some team members dependent on the leader's guidance, thus reinforcing on-the-job training. These findings suggest that the checklist served not only as a tool for improving protocol compliance—as originally intended by its creators—but also as a cognitive aid that helped teams communicate, collaborate, reflect, and make decisions more efficiently. In other words, using the checklist meant more than just checking off items and ensuring each step was completed. Designers of digital cognitive aids for emergency medical work should therefore consider how to preserve these team practices while also fulfilling the primary goal of a checklist. Below we provide a few directions for how these digital aids could be designed to maintain functionality and affordances of paper checklists. The goal is to help resuscitation team members maintain awareness about the flow of work and what their colleagues are doing, while facilitating seamless communication and information sharing.

Distribute patient and process monitoring across the entire team. The resuscitation checklist was designed for the physician leader as a way of ensuring protocol compliance. As such, the checklist information was accessible only to checklist administrators, that is, leaders. While this approach aligns well with the general use of checklists [10], we saw entire teams benefiting from the checklist information. Like whiteboards, checklist can be considered as an information container that preserves information about team tasks, activities and decisions made during the resuscitation; information recorded on the checklist is expected to be persistent and visually visible all the time, much like information on the whiteboards, unless intentionally obscured [20]. Similarly, providing teams with constant visual access to the checklist information may help sustain and even encourage some of the positive changes in team dynamics, such as process reflections and joint decision making, while minimizing negative effects. For example, a system that makes the checklist information available to the entire team may make team members with less experience (especially surveyors who are still in training) proactive and less dependent on leader's instructions, as the status information will now be distributed across the entire team. Furthermore, by seeing the checklist information, other team members can collectively monitor compliance with the protocol, thereby reducing a chance for deviating from the protocol or skipping tasks. This collective monitoring for protocol compliance is also in line with general groupware design principles that recommend embedding a group process in software to provide structure to the group's activity and ensure that the process is followed [8]. Public display of the checklist information could also improve documentation by allowing the scribe nurse to compare data between the flowsheet and checklist display for accuracy and consistency.

Although administering the checklist did consume leaders' attention, we found that it did not interfere with leaders' performance, allowing them to frequently look at the vital signs monitor and engage with the patient when needed. Even so, the increased number of looks at the monitor may also be the result of a cognitive burden of using or learning how to use the checklist. For example, the leaders might have had difficulty holding the status of the patient in short term memory, so they increased their references to the monitor to be able to keep track of the patient trajectory. After all, we did observe leaders jotting down vitals information on the checklist for easier information access. While these are just hypotheses, we believe that public display of the checklist information would help unburden the leader by distributing process monitoring across the entire team.

In short, the distributed access to checklist information among team members would allow for continuous and collective monitoring for the protocol compliance, enhanced situation awareness, and collaborative information seeking and decision making. As prior studies of time-critical, high-reliability domains have shown, increased heedful interrelating and mindful comprehension often lead to decreased errors during collective mental processes [21]. We believe that making the checklist information available to the entire team, thereby supporting the notions of collective mind and heedful interrelating, can help improve the efficiency and quality of their overall performance, as well as patient safety.

Preserve good communication redundancy. Overall, we observed that the checklist increased the amount of leaders' communication—checklist scenarios had more information requests, task assignments, and reports, than control scenarios. The checklist served as a natural script by which leaders communicated, prompting them to regularly check in with physician surveyors and other team members, and ensure task completion. These findings highlight the role of the checklist in ensuring information completeness, and facilitating team communication and collaboration. Still, we observed some communication issues that emerged as a result of the checklist use. Requests for information, for example, intensified during checklist scenarios. In fact, we can consider most of these requests as a byproduct of the checklist because they referred to the previously reported information. To be able to check off an item, the leader had to explicitly confirm a task completion. As a result, additional inquiries, triggered by the checklist, increased the amount of chatter and noise in the room while also leading to communication redundancy. Although some of this redundancy can be considered as "superfluous" and "wordy" [2], it can also benefit medical work by ensuring that all information is heard and recorded. Further study is needed to determine the extent to which these communication patterns improve teamwork as opposed to simply producing an overhead. Cabitza et al. [2] argued that technology could preserve the usefulness of redundancy and at the same time relieve actors of any additional efforts they make to ensure task completion. Public display of the checklist information could then help preserve good data redundancy while potentially reducing repetitive requests for confirming task completions. Furthermore, our findings showed that leaders who used the checklist inquired more frequently about patient status, process status, and equipment and medication availability. An implication here is that public displays, in addition to showing task completions, could also include status information about the most frequently requested items.

Augment leader-cognitive aid interaction while preserving affordances of paper. As we described above, the paper checklist allowed leaders to jot down notes and important patient data during the resuscitation. Though not widespread in the study, this practice implies that informal note taking is important because it allows for easier information retention. This simple advantage of the paper record is also one of the reasons why paper-based systems still persist [9]. It is therefore important that future cognitive aids take into account this function and allow informal data capture. An additional feature could allow the leaders to keep these informal notes hidden and then retrievable when needed. Digital cognitive aids could also allow leaders to indicate abnormal findings by using visual primitives (e.g., attention icons, circles) to draw the attention of the team and help prioritize treatments. Finally, the checklist administration method made a difference in most leadership behaviors, emphasizing the importance of the interaction mode when designing for future interactive cognitive aids. The challenge-response checklist—when the leader called for a pause at various times during the event and then went through the checklist—took more time to administer than the do-list checklist. The pauses, however, helped teams reflect on the process and get on the same page, which is a feature worth preserving. In contrast, the do-list method required more frequent looks and interactions with the checklist. Even so, the distribution of the leaders' communication behaviors during do-list scenarios was similar to that of controls (Figure 2), suggesting that the do-list administration method may fit better with the overall dynamics of emergency medical work.

6. CONCLUSION AND FUTURE WORK

In this paper, we examined the use of a paper checklist introduced to prepare for patient arrival and for use throughout patient evaluation in a regional trauma center. Our dataset comprised video recordings of 48 simulated resuscitations in which the checklist was tested for its impact on team performance. The simulations afforded an ecologically valid and controlled setting for understanding how the checklist was used and the effects it had on leadership behaviors and team dynamics. Based on these findings, we offered several directions for how interactive cognitive aids could be designed to support practices that emerged as a result of the checklist use. Our study, however, was based on observations and video review of the initial use of the checklist. To complement this data, we are planning in-depth interviews to learn about clinicians' perspectives on the checklist effects. The resuscitation checklist is now incorporated in the actual patient care and its use has been routinized, so we plan to evaluate the extent to which the first-time use of the checklist differs from an evolved, routinized use of the checklist. We also plan to conduct a longitudinal study to examine how some of the effects we observed in simulations play out in the context of patient outcomes and protocol compliance in the real-world scenarios.

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