Distributed cognition in the heart room: How situation awareness arises from coordinated communications during cardiac surgery

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Abstract

To help ensure successful outcomes of open-heart surgery, surgeon and perfusionist must coordinate their activities during management of cardioplegia. This research aims to understand the basis for this coordination. We employed the framework of distributed cognition and the methodology of cognitive ethnography to describe how cognitive resources are configured and utilized to accomplish successful cardioplegia management. Analysis identified six types of surgeon–perfusionist verbal exchange which collectively enable robust system performance through (a) making the current situation clear and mutually understood; (b) making goals and envisioned future situations clear and thereby anticipated; and (c) expanding upon the activity system's knowledge base through discovery and sharing of experience. We argue for the “activity system” as the appropriate unit of analysis, and distributed cognition as a powerful theoretical framework for studying the socio-technical work of health care.

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1. Introduction

The resources available to an open-heart surgery team are limited by the constraints of time, space, expertise, perception, memory, attention, and equipment, among other things. In cardiac surgery, time is critical. Delays in key stages of open-heart procedures can cause irreversible damage to the heart or other body systems. In addition, minimizing the total duration of the surgery is known to be a key ingredient of successful outcomes. To achieve the goals of open-heart surgery requires coordination among surgery team members and between these actors and the tools and technologies that support their work. In order to achieve this coordination, unfolding events must be expected and the resources for appropriate responses to those events must be available to actors. In this paper, we consider the means for this coordination and how they produce situation awareness as a natural byproduct.

We report on an ethnographic study of cardiac care conducted to understand the formal and informal practices that health professionals employ to ensure safe and effective care. We used cognitive ethnography [1] to understand how system resources are configured and utilized to accomplish successful cardiac surgery and prevent adverse events. The primary unit of analysis in this research is the activity system comprised of actors and tools, together with rules and understandings that guide interactions in a structured environment or workspace. In the cardiac surgical context, we consider the activity system to be a multidisciplinary group of health care professionals who use an array of tools to complete a surgical procedure or case in a highly configured “heart room.” Typically, the group consists of: a surgeon; a physician’s assistant (PA); a perfusionist; an anesthesiologist; two “scrubs” (nurses or scrub technicians) who assist within the sterile field; one nurse circulator who assists outside the sterile

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field to provide supplies for the team; and one nurse manager who provides a “bridge” to resources outside the heart room.

While explicit awareness of the situation by team members can be important, it is not possible for all members to attend to all information or to have access to all resources that constitute each situation during the case. Instead, an organization and division of cognitive labor creates the means by which information is attended to and processed, and by which appropriate actions are taken by team members in order to accomplish tasks and achieve goals. Considered across time, this organization of cognitive labor enables the team to accomplish complex tasks reliably and safely. It also sets up requirements for coordination among team members and with their tools, and with the highly structured task environment in which they work. Some of this coordination is accomplished through explicit communications that may clarify aspects of the current situation or that generates expectations about an unfolding situation. Below we consider the activity of the team in terms of the framework of distributed cognition and report on the nature of communications utilized by the team to conduct a specific portion of the surgery. We argue that situation awareness is a consequence of this coordinated activity and that the focus for research on human performance in complex socio-technical systems should be on describing and understanding the organizing principles of this coordination.

2. Background

Cognitive science has a long history of studying the relationship between individuals’ internal organizations and their behaviors in terms of information processing properties of the central nervous system [2]. Distributed cognition, by contrast, treats the activity system rather than the individual as the unit of cognitive analysis and considers the properties of this system that determine performance [3–5]. In particular, we treat the ‘propagation of representational state’ through activity systems as explanatory of cognitive behavior and investigate the organizing features of this propagation as an explanation of system and human performance. A representational state is a particular configuration of an information-bearing structure, such as a monitor display, a verbal utterance, or a printed label, that plays some functional role in a process within the system. Processes of the activity system propagate representational states across diverse media and thereby achieve effects within the environment. System behavior results from the coordinated operation of these processes. An example is the medication ordering and administration processes in an Intensive Care Unit [6]. An order written in compact form by a physician is often expanded upon by the unit secretary, clarified by the pharmacist, and potentially refined by the administering nurse to meet the needs of an evolving situation. Each of these agents will employ various artifacts, technologies, domain knowledge, organizational policies, and implicit understandings to transform, interpret, and act on the order, ultimately resulting in administration of medication to the patient. System behavior—care for the patient—results from the coordination of processes that propagate representational state across diverse media. The organization of this propagation provides a focus for empirical investigations to understand the bases for human performance.

2.1. Managing cardioplegia during open-heart surgery

During open-heart surgery, a heart–lung bypass machine assumes the blood circulatory functions for the patient. It also controls the flow of blood solutions to the heart, which is temporarily separated from the circulatory system. The perfusion activities of a cardiac surgery team primarily involve the surgeon and a member of the team called the “perfusionist.” The perfusionist physically controls the heart–lung bypass machine from a location behind the surgeon (see Fig. 1). Cardioplegia is an induced arrest of the patient’s heart to permit enhanced manipulation of the heart and nearby structures during the procedure. Following arrest, the heart–lung machine takes over the function of circulating oxygenated blood through the patient’s body. A cardioplegia solution is used within a special circuit of the heart–lung machine to perfuse the patient’s heart in order to oxygenate and regulate the temperature and activity of the heart. Throughout the majority of the procedure, the surgeon is primarily focused on manual manipulations of the patient’s chest and heart, while the perfusionist is primarily focused on the functioning of the heart–lung machine. Each has access to information that the other does not: the surgeon has visual access to the surgical field, and tactile information about the temperature and compliance of cardiac tissue, while the perfusionist has visual access to the various displays and controls of the heart–lung machine, as well as other displays and equipment not visible or accessible to the surgeon. Successful execution of the cardioplegia initiation and management tasks requires effective integration of this information. Communication between surgeon and perfusionist serves to coordinate the joint activity of cardioplegia management, which recurs during the critical period that the patient’s heart is at rest.

Cardioplegia solution is delivered in discrete “doses” or boluses, which can differ in volume, rate of flow, contents, and temperature throughout the procedure. The first bolus is delivered when bypass is initiated and the patient’s heart is brought to a state of arrest. Other boluses, aimed at protecting the heart muscle from damage, are interspersed throughout the period that the patient is on bypass. The primary constraints on the timing and size of these doses are (a) the need to keep the heart muscle perfused with oxygenated blood, (b) the need to keep the heart still and hypothermic (cold), (c) the need to minimize the duration of being on-bypass, and (d) the need to not interfere with
manipulations required by the surgery itself [7]. Meeting all of these requirements is the task of cardioplegia management and it is accomplished by the coordinated efforts of the surgeon and perfusionist. While the surgeon is the one to call for the onset and completion of a cardioplegia bolus, it is the perfusionist who operates, maintains, and is the expert on the bypass machine that delivers the solution. The precise rate of cardioplegia solution perfusion is not typically a focus of concern, however the perfusionist will track the volume of cardioplegia solution circulation that has been delivered in the bolus (typically taking five to ten minutes) and it is the perfusionist who knows and physically controls the temperature and the ingredients of the solution delivered.

During surgery, the surgeon stands directly adjacent to the patient, typically with his hands in the patient’s chest and his attention focused on manual (and tool-mediated) manipulations of the heart. The perfusionist occupies the space behind the surgeon, and the bypass machine sits between the two. The surgeon’s back is to the perfusionist, and the perfusionist and bypass machine both reside outside of the sterile operating field, as shown schematically in Fig. 1. Although the perfusionist’s duties will take him away from the bypass machine on occasion (for example, to run blood-gas and other blood tests), he is seated at the bypass machine controls during significant portions of the surgery. Although the bypass machine can be configured in many ways, one of four circuits (operated by a dial controlling an independent pump) is typically used for cardioplegia. A small monitor attached to the right side of the machine shows the perfusionist the amount and temperature of the cardioplegia solution during delivery to the heart. The perfusionist is also responsible for the setup and maintenance of hemodynamic monitoring devices which measure pressures that are displayed on two large color monitors, one at the head and one at the foot of the surgical table, as shown in Fig. 1. These pressure readings display important information about the patient’s blood circulation and are constantly monitored by surgeon and perfusionist, as well as other team members.

Throughout a procedure, surgeon and perfusionist each have only partial access to the information that is relevant to a successful outcome. Furthermore, each must perform distinct actions, requiring distinct areas of expertise, yet these actions must be coordinated in order to achieve shared goals for the surgery. This coordination is accomplished through cognitive means that enable the necessary sequencing of actions to accomplish tasks and goals in a dynamic environment. In short, the mechanisms underlying this coordination serve to control a complex, dynamic activity system.

During perfusion and cardioplegia management, minor deviations, problem identification, and corrections to prior actions are commonplace and expected aspects of coordinating the complex activities involved. In Table 1 we present a relatively ordinary, although by no means uneventful, stream of events in cardioplegia management in order to give an overview of the tasks involved. The transcript begins following successful cardiac arrest, with administration of a second bolus of cardioplegia solution. The surgeon notices that the heart is filling up with blood, a phenomenon that suggests the heart–lung bypass circuits are not functioning properly because the heart should be isolated from the main circuit perfusing the patient’s body. A series of communications and actions follow, with the aim of identifying the cause of the problem and returning the system to a normal, more desirable, state.

As seen in the transcript of Table 1, the sequencing of actions is sometimes accomplished through explicit announcement of steps to perform (“up on green”) but also happens by establishing target states (“empty the heart”) and
by actors making explicit their expectations for action generated by reading the current situation, as demonstrated in the following three turn verbal sequence (see Time 3:19 in Table 1):

1. [P] “Getting more activity” (referring to the visual display of a faint heart beat on the monitor);
2. [S] “Might need more potassium”;
3. [P] “I just gave some.”

As in other realms of human activity, coordination in the heart room is accomplished through the appropriate sequencing of actions. This sequencing accomplishes tasks required to achieve goals. In addition, attention to the sequencing of actions allows actors to establish the meanings of events (often through reading each others’ actions) and thereby to understand the urgency (and appropriate recovery methods) that pertains when deviations from expected events occur. That is, this organization to the activity yields robust system properties and gives rise to situation awareness.

In the remainder of this paper we seek to characterize the activity of cardioplegia management in terms of a verbal “coordination device”—a pattern of exchanges that

<table>
<thead>
<tr>
<th>Time</th>
<th>Transcript</th>
<th>Tasks/Goals</th>
</tr>
</thead>
</table>
| 0:00 | S: Give cardioplegia Green off  
    P: Green is off | Avoid contamination of main supply (‘Green’ and ‘vent’ refer to the suction circuit, and cardioplegia solution should not be suctioned into the general blood supply) |
| 0:12 | S: Empty the heart  
    S: The heart’s full for some reason  
    P: I think it’s the way you’ve got it cranked. (Perfusionist suggests a kink in the line may be the problem)  
    S: Not now. I’ve got a straight shot. Still full  
    P: Emptying out?  
    S: It is now  
    P: OK  
    S: Are you holding volume?  
    P: No | Restore cardioplegia (oxygenates heart muscle and maintains hypothermic cardiac arrest)  
Keep heart from filling with blood (full heart is an indication that bypass circuits operating improperly) |
| 0:35 | S: You giving the plege?  
    P: Yeah. And vent’s off | Identify graft locations |
| 1:07 | S: Let us know when 300’s in  
    P: Yes, sir. (sound is degraded : Perfusionist tells surgeon that 300’s in and plege is off. Surgeon confirms, ‘thank you.’) | Drain full heart |
| 1:18 | S: Creep your green  
    P: Green is creeping  
    (Surgeon is looking for a coronary artery on which to sew a bypass graft) | Fully isolate the heart’s perfusion circuit (by adjusting the aortic cross-clamp) |
| 2:36 | S: (You sure) your vent’s on?  
    P: Yes, sir  
    S: Turn it up higher, way higher  
    P: Way higher | Re-administer bolus of cardioplegia (now that the cardioplegia circuit is believed to be intact) |
| 2:46 | S: Surgeon, speaking softly to PA and scrub nurse beside him explains what he thinks is causing the heart to fill, ‘…cross-clamp is not all the way across.’  
    P: Green is off  
    S: Yep. Give your cardioplegia again  
    P: OK  
    S: Green off  
    P: Green is off | Maintain cardiac arrest |
| 3:19 | P: Getting more activity. (Gives Potassium to arrest the heart)  
    S: Might need more Potassium  
    P: I just gave some  
    S: Clamp must have been leaking or something. That was bleeding way to briskly for just pulmonary venous return | Stop cardioplegia, resume other surgical tasks |
| 4:09 | S: OK, you all in?  
    P: Almost. There you go. It’s in. And off  
    S: (…) your green  
    P: Green’s back on | |

S, surgeon; P, perfusionist; italics, analytic or other commentary; (...), inaudible.
serve coordinating functions for the system—evidenced in surgeon–perfusionist communications. In the next section we discuss a theoretical foundation for this characterization. Then we articulate the empirical methods we utilized to discover this coordination device. Following this, we present the findings from our analysis of cardioplegia management in the heart room. Finally, in Section 5 we consider what our findings tell us about human performance generally and how this could inform technology and process designs intended to enhance that performance.

2.2. Using distributed cognition to understand activities in the heart room

The activity system, our primary analysis unit, is comprised of actors and tools, together with rules and understandings that guide interactions in a structured workspace. The activity system engages in activities oriented by the shared goals of its actors, who typically share a history of interaction. An activity is oriented by one or several goals, for instance “oxygenate the heart tissue.” Component tasks attain these goals through use of coordination devices. For example, a shared protocol for communicating goals is a coordination device that enables well-understood sequences of actions. Coordination devices are constituted by particular arrangements of resources (information structures and processes which can act upon these structures) that are available within the system.

Pre-configuration of the heart room provides an example of a coordination device. The scrubs in this cardiac surgery unit will spend up to 2 h configuring the heart room prior to the start of surgery so that the supplies and instruments they expect to use, or may need to use, will be easily available in the right place and at the right time during the procedure. Pre-configuration is dominated by the tasks of carefully transferring, unwrapping and laying out supplies and instruments from a mobile supply cart (outside the sterile field) onto a set of tables (ready for use in the sterile field) [8]. These tables are then arranged within the sterile surgical field at the start of the surgery (see Fig. 1). The final arrangement of instruments is coordinated with the surgeon’s needs and is based upon the scrubs’ routines for knowing the surgeon’s preferences, the sequencing of the surgical tasks, and knowing where to get the instrument/ tool when it is needed. The entire setup constitutes a coordination device because it establishes the means to efficiently accomplish a sequence of actions required by the surgery.

During the procedure, when the surgeon holds out his hand, he is signaling his need for a particular instrument. Sometimes, he will vocalize this request by naming the tool, but often he knows that the scrubs’ attention to his work, together with the work that went into configuring the heart room, makes this unnecessary because the tool is “at hand” and therefore simply holding up his hand suffices. The effectiveness of this action is determined by a particular configuration of resources that was established during setup, prior to the beginning of the surgery. A complex or novel procedure, an unexpected or emergent state of the patient, or involvement of a new or inexperienced team member may require resorting to more vocalization by the surgeon than is usually necessary to convey this need, or it may require the team retrieving a tool from the supply room to meet the need. In this example, the preconfigured heart room provides a set of resources (e.g., specific tools and awareness about their organization and purpose) promoting coordinated action. At the same time, and by definition, it also imposes constraints on action. The relationship between scrub’s understandings about the set of tools and the physical organization of the tools themselves is what enables the coordinated action. Simultaneously, this arrangement creates a need to elaborate when a request is made for some tool not included in the physical set or not recognized by the scrub when attending to the request.

In the framework of distributed cognition, the relationships among resources in a particular arrangement are referred to as constraints, and thus a coordination device can also be referred to more generically as an “arrangement of constraints and resources.” Coordination devices typically function through their capacity to control the propagation of representational states through the system, thereby facilitating actions and achievement of states of the environment-plus-system that ultimately attain the shared goals of actors. A checklist performed in the cockpit of a commercial airliner prior to takeoff is an institutionally enforced coordination device that ensures a proper configuration of the aircraft for safe takeoff. It entails not only a sequence of terms (that may be variously instantiated in paper, electronic displays, and mechanical forms of the checklist [9]) but also a procedure for invoking, attending to, and acting upon these terms and the states of the aircraft that they represent [10]. Improvements in system performance through the use of checklists as a coordinating device have also been reported in surgical care [11].

Representational states are particular configurations of physical media (e.g., verbal utterances, pen marks on a form, patterns on a display device, or the position of a control knob) that (via engagement by interpretive processes) model the properties of other objects or events within the system or its environment [4]. Finally, an interpretive process is one that can systematically transform structure in one medium into structure in another medium. The propagation of representational states across diverse media provides the system with information, constrains action upon or using that information, and thereby determines system behavior. Fig. 2 shows how these various entities are related in our interpretation of the framework of distributed cognition.

In short an activity system is an instance of a complex dynamic system, and coordination devices represent the system’s means for controlling its behavior through determining the nature of information flows through the system. Using this model to orient our investigation of activities in
the heart room, we focus on the highly structured interactions between surgeon and perfusionist during cardioplegia management. As detailed in the next section, the organization of these interactions (a subset of the complete heart room activity system) is evident in a set of highly patterned communications between these two team members performing this activity. In other words, these patterns of communication entail a coordination device—an arrangement of constraints and resources that control a propagation of representational states through the activity system and thereby enable effective sequencing of actions necessary to accomplish tasks and achieve goals.

3. Methods

As part of a study of health professional work practices that contribute to patient safety, and with approval by the Institutional Review Board, we collected audiovisual recordings of 20 open-heart surgical cases involving both coronary artery bypass surgery and heart valve replacement performed in a dedicated heart room within a larger suite of operating rooms (OR) at a single institution. The heart room functions somewhat independently from the remainder of the surgical suite and is staffed by a select group with significant history working together, including several surgeons and perfusionists, two physician’s assistants, a dozen anesthesiologists, a half-dozen first scrubs, and a number of second scrubs and circulating nurses drawn from the staff of the larger OR suite as needed.

In order to elucidate the functional properties of this activity system, we employ methods that highlight how information flows through the system in support of task work. These methods are ethnographic because they rely heavily on the naturalistic field study of work practices. The methods are also cognitive because we seek data that allows us to attribute representational states and their effects upon action. Our work proceeded from a phase of very general ethnographic observation and broad data capture, to analysis of a specific task (cardioplegia management, in this case) involving a subset of the activity system for which we could comprehensively capture relevant events.

We recorded activities simultaneously from three camera angles to get coverage of nearly the entire heart room. We also spent about 200 h observing in the heart room to learn about cardiac surgical care. Our multidisciplinary research team included an internal medicine physician

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In reviewing the procedure maps, we next identified general patterns, delineated tasks conducted by actors, and generated questions for clarification. Importantly, analysis of a possible coordination device requires elaborate task-analysis. Therefore, we required data revealing the structures, resources, and processes utilized to accomplish tasks. In this step of analysis we: identified tasks of interest; reviewed several examples of each task; identified technical questions and consulted fieldnotes, surgery team members, textbooks, and other information sources for more information; produced descriptive accounts of possible coordination devices for further analysis.

The next step used the procedure maps to identify specific video segments addressing a focused realm of activity that involves a possible coordination device. The focus for analysis could be a task, a specific resource utilized to accomplish tasks, or a certain subset of actors in the system. We noticed highly patterned communication practices during cardioplegia management and decided to restrict our analytic attention to the surgeon and the perfusionist on the team and their interactions in the tasks of cardioplegia administration. With this task focus in hand, we augmented our knowledge base with review of taped cases, informal interviews with heart room staff, and consultation of written materials on the perfusion aspects of heart surgery. We next determined the set of cases, and thus the data, to include in our analysis. We read through the procedure maps for each included case, and created a preliminary list of activities and events involved.

Specific events captured on video were further segmented into video “clips” and then transcribed to reveal the details of verbal and other behaviors (see Table 2 for an example). These elements form the basis for comprehensive coding of the events as types of exchanges. By viewing the transcripts alongside video clips that showed the surgeon and perfusionist’s interactions and tasks in detail, we gained a fine-grained understanding of the exchanges

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### Table 2
Illustration of video data analysis process

<table>
<thead>
<tr>
<th>Time</th>
<th>Procedure map description</th>
<th>Handwritten annotations</th>
<th>Transcript</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:13:25</td>
<td>Surgeon says green off, then flush cardioplegia</td>
<td>S → P Direction, action, confirmation</td>
<td>S: Green off</td>
<td>DIRECTION</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Vent off</td>
<td>P: Green is off</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Flush plege</td>
<td>P: Flush cardioplegia</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Cross clamping (flow down, clamp on, plege up)</td>
<td>S: Off</td>
<td>DIRECTION</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Arrest</td>
<td>P: Off</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Report system status</td>
<td>The surgeon asks for and receives the aortic cross-clamp from a scrub nurse</td>
<td>DIRECTION</td>
</tr>
<tr>
<td>0:13:45</td>
<td>Surgeon asks for cross-clamp. Then says flow way way down. Then clump is on, up on plege. Perf confirms all these steps</td>
<td>S: Flow way down</td>
<td>S: Flow way down</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P: Way down, sir</td>
<td>P: OK, flow’s back up</td>
<td>STATUS &amp; DIRECTION</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S: Clamp is on. Up on your plege</td>
<td>Plege is coming</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P: OK, flow’s back up</td>
<td>S: Fibrillating</td>
<td>ALERT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S: We have a nice arrest</td>
<td>P: Thank you</td>
<td>STATUS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P: Thank you (…)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0:14:15</td>
<td>S1 asks for new gloves. Surg says heart is fibrillating. Surgeon placing cold ice slush on heart. Tells perf they have a nice arrest</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
utilized to administer cardioplegia as it occurs in the context of the broader surgery activities. Based on a general review of cardioplegia-related events, research team members developed a preliminary coding scheme for types of communication between surgeon and perfusionist. Next, we independently coded the communications between surgeon and perfusionist in each segment according to the preliminary classification scheme. We refined the scheme through a process that resolved discrepancies in our coding and refined our definitions of codes. This process was repeated (with new data, over several weeks) until we reached agreement in our coding of the surgeon–perfusionist communications. These final codes were then applied to characterize surgeon–perfusionist communications around cardioplegia management within the complete set of initial segments. Agreement across the coders gives us confidence about the method’s validity. Examining the contexts in which each type of exchange occurs, we arrived at general descriptions of each type of communication exchange and of the roles these play as coordination devices in the activity system.

4. Findings

In our analysis of communications between surgeon and perfusionist during cardioplegia management we identified six distinct patterns that we are able to relate to functional properties of the activity system. We treat instances of these communications as “exchanges” between surgeon and perfusionist. Each exchange involves one or more “turns” or contributions delineated by changes in role from addressor to addressee for each participant. Furthermore, each exchange is focused on some “task” or specific aspect of the work. Although there are many tasks that are accomplished in what we analyzed, the exchanges all appeared to us to fall into six distinct types, that we labeled “direction,” “goal-sharing,” “status,” “alert,” “explanation,” and “problem-solving.” Each type plays a specific functional role in the system by enabling effective sequencing of actions that accomplish tasks and achieve goals. Below we describe each type of exchange and the roles it plays in enabling control of the activity system.

4.1. Direction—command an action that seeks to transition the activity system to a new state

Directions are common and sometimes very formalized forms of communication in the OR setting. Their degree of formality increases with engagement in high-risk or hard to reverse actions, especially actions that are not fully accessible to multiple agents in the activity system. Examples include administering certain medications that alter blood coagulation (protamine, heparin) or adjusting the settings of machines that only one operator can control, such as cautery, laser, or perfusion machines. With respect to perfusion activities, the surgeon typically initiates directions. Directions start by explicitly commanding an action and thereby, when acted upon, achieve a transition to a new system state through performance of the commanded action. The initial turn, entailing a request for action, is typically followed by a turn that confirms the action taken. A simple example of this exchange is:

<table>
<thead>
<tr>
<th>Excerpt 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeon:</td>
</tr>
<tr>
<td>Perfusionist:</td>
</tr>
</tbody>
</table>

The initial turn of a direction exchange, the request for action, is succinct and relatively simple. For example, surgeons often ask perfusionists to adjust the flow of various fluids in the cardiopulmonary bypass system by saying, “up on green,” or “flow way down.” Less commonly, the surgeon uses the perfusionist’s name as part of the request or explains the reason for the action requested, as in “Come up on your yellow, [name of perfusionist], we’re trying to...” Confirmations of requests (in addition to the non-verbal information present in changes in the system state, such as a perceptable change in the compliance or volume of the heart tissue), can take several forms. The request may be repeated, often simultaneously with the action, as in “flow way down.” The changed status may be communicated, as in “flow is down.” Statements such as “thank you,” or “yes sir” can simply indicate acknowledgment of the command, while implying completion of the action. Finally, confirmations may also request some additional information, such as the desired timing of the action, as illustrated in the following excerpt:

<table>
<thead>
<tr>
<th>Excerpt 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Surgeon:</td>
</tr>
<tr>
<td>2 Perfusionist:</td>
</tr>
<tr>
<td>3 Perfusionist:</td>
</tr>
<tr>
<td>4 Surgeon:</td>
</tr>
</tbody>
</table>

4.2. Goal sharing—create expectation of a desired future state

This type of exchange sets up the expectation of reaching a future or target state, as opposed to focusing on the specific pathway or sequence of actions required to reach that target. For example, the perfusionist may ask the surgeon about his intentions for future cardioplegia in order to prepare for the next phase of the procedure. In one exchange, a perfusionist and surgeon shared their goals regarding an unusual type of cardioplegia administration
that neither had practiced very recently. The perfusionist suggested giving a bolus of warm cardioplegia before releasing the cross clamp. The surgeon said this was a good idea. Then the perfusionist inquired, “Is that going to be our next dose, or will it be cold?” The surgeon responded that the next dose would be cold. After this goal sharing exchange, the surgeon and perfusionist were able to coordinate the specifics of cardioplegia administration smoothly because they had established a common understanding about the series of expected states for the system.

4.3. Status—create shared understandings about the current state

This type of exchange is often initiated by a request for information (a query). In the following sequence, two status exchanges (lines 1–4) request information that leads to a direction (lines 5–6):

Excerpt 3

<table>
<thead>
<tr>
<th>Line</th>
<th>Surgeon</th>
<th>Perfusionist</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surgeon</td>
<td>How’s your myocardial probe?</td>
</tr>
<tr>
<td>2</td>
<td>Perfusionist</td>
<td>29–8 [29.8?]</td>
</tr>
<tr>
<td>3</td>
<td>Surgeon</td>
<td>How much you got?</td>
</tr>
<tr>
<td>4</td>
<td>Perfusionist</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>Surgeon</td>
<td>Just let me change it over to retrograde, we got a nice arrest—</td>
</tr>
<tr>
<td>6</td>
<td>Perfusionist</td>
<td>Alright</td>
</tr>
</tbody>
</table>

Status information may be requested through a query, as in lines 1–4 of Excerpt 3, or just simply volunteered without a specific request. For instance, the perfusionist will often report without prompting, at the appropriate point in the procedure, that cardioplegia setup is functioning as desired. In this case, the report is expected by the surgeon but not explicitly requested. Another common reason for volunteering information is to alert an actor to a routine change in system state that they cannot see, but which is important to know. For example, surgeons routinely provide a status report of “temp probe is out” when they remove the temperature probe out of the heart. By doing so, they are telling the perfusionist that changes in the display (temperature rising) are not the result of myocardial warming but rather the result of a change in the measuring device’s location.

Volunteering information can also be motivated by recognition of a precondition for action. In other words, an event that produces information in the form of a status exchange sets up an expectation for a specific action. For example, in line 1 of Excerpt 4 the perfusionist provides a status report to the surgeon. The perfusionist draws upon general experience and the particulars of the case. He notes parameters on the perfusion machine display that are likely to indicate that sufficient cardioplegia has been given. The perfusionist communicates these parameters to the surgeon in a status report, and the status report results in a direction (lines 2–3):

Excerpt 4

<table>
<thead>
<tr>
<th>Line</th>
<th>Surgeon</th>
<th>Perfusionist</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perfusionist</td>
<td>Good cooling. We’re down to 17.2 with 500 of cold</td>
</tr>
<tr>
<td>2</td>
<td>Surgeon</td>
<td>(Stop at) a liter</td>
</tr>
<tr>
<td>3</td>
<td>Perfusionist</td>
<td>Aiming for a liter of cold</td>
</tr>
</tbody>
</table>

This kind of status report contains an implication that a given action ought to happen. In other words, a status exchange can have the effect or function of indirectly commanding an action (i.e., it also functions as a direction) via the expectations that are associated with the current state. As another example of this, the surgeon’s status report, “Going on bypass” entails a request for the perfusionist to carry out a number of sequential, relatively fixed (and critical) actions to initiate cardiopulmonary bypass.

4.4. Alert—convey abnormal or surprising information about the current state

Alerts and status reports are very similar exchanges. However, alerts are generated by events that create a perceived deviation from the expected or desired system state. As such, the information offered can imply consideration of a deviation from the expected actions to be taken. For outside observers, it is sometimes difficult to distinguish between the two. For example, if the heart resumes beating slightly when it is required that it be completely stopped, the surgeon will alert the perfusionist to this event, saying “we’re getting some activity.” This could be considered an alert because the phenomenon reflects an undesirable state. However, this situation occurs quite frequently and there are a number of routine steps that the perfusionist will take to bring the system back to its desired state (operating with cardiac arrest). We believe that despite some areas of overlap, the general distinction between status reports and alerts are clear to actors in the system because of their experience with the procedure, their history of shared interactions as members of a close-knit heart surgery team, and their reactions to alerts as unusual system states. Consider this stretch of communication about an abnormal system state.

Excerpt 5

<table>
<thead>
<tr>
<th>Line</th>
<th>Surgeon</th>
<th>Perfusionist</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surgeon</td>
<td>I had to vent the right heart. You had good drainage in the atrium but the right heart wasn’t (…)</td>
</tr>
<tr>
<td>2</td>
<td>Perfusionist</td>
<td>Huh… (adjusts, checks equipment)</td>
</tr>
<tr>
<td>3</td>
<td>Surgeon</td>
<td>Looks like you’re getting some (…) on the aorta, too</td>
</tr>
</tbody>
</table>

(continued on next page)
In this fairly complex sequence, the surgeon communicates alerts to the perfusionist (“Looks like you’re getting some…”). The perfusionist also communicates alerts to the surgeon (“Sinus pressure’s up. It looks like 92,” and “It’s a little intermittent.”) Each of these alerts has the immediate function of signaling an abnormal system state to an actor who cannot observe the phenomenon being reported. The surgeon tells the perfusionist about what he actually sees and feels in the patient’s heart. The perfusionist tells the surgeon about the data displayed on the perfusion machine. Each of these speech events acts as an alert because it projects a need for possible corrective action.

4.5. Explanation—create a rationale for the current state

Explanations are common communication exchanges in the OR. They can address relatively simple issues, such as criteria for deciding how much cardioplegia solution to administer (Excerpt 6, line 4):

Excerpt 6 (continued)

| Perfusionist: You wanna go to 800 on her? |
| Surgeon: How much you got in? |
| Perfusionist: 400 |
| Surgeon: Let’s go to 750. She’s got a good arrest, ventricle’s empty. You can see it on the echo, that empty ventricle, it’s not distending |

In Excerpt 6, the surgeon could have accomplished goal sharing by simply stating, “let’s go to 750.” However, his explanation of the rationale for this decision creates shared understanding of the situation as well as his reasons for taking particular actions. In explaining his decision, the other agents learn about the particular case they are performing as well as decision-making criteria about cardioplegia in general.

Explanations are offered to reduce uncertainty about the current state and the pathway that lead to it. For instance, the surgeon may be “heads down” during some prolonged manipulation of the heart that is outside of the awareness of the perfusionist and other team members who are not looking directly into the patient’s chest. Following such a period, we observed that explanation exchanges functioned to reestablish shared understanding about system state (e.g., see Excerpt 5, line 1). In Excerpt 5, explanations of the possible causes for the system state (“It looks like 92. Is the heart up?”), are interwoven with alerts about the situation. Taken together, these alerts and explanations function to piece together a situation that is only partially accessible to any one agent. These interlinked exchanges represent another type of communication, which we call problem solving.

4.6. Problem solving—reason toward a more complete understanding of the current state

This type of exchange appears to be prompted by uncertainty about the current situation or about the possible courses of action to pursue next. Problem solving typically involves a series of turns that include alerts, explanations, directions, status reports, and goal sharing. Actors state facts that highlight uncertainty about the system state (e.g., facts which are in conflict with understandings or held assumptions, or which are highly problematic) in an effort to explain the facts, create coherent understanding, and reduce uncertainty. Problem-solving communication generally spans a longer time frame than the other types of communication described so far. Problem-solving communication is often interrupted by exchanges that address other issues or other actors. For example, the surgeon may address the scrub to request equipment that is unrelated to the problem being explored. However, problem-solving communication about cardioplegia rarely transcends the surgeon–perfusionist dyad, although it may draw in other agents if they can provide clarification or information that is not accessible to the surgeon–perfusionist dyad.

In the extended example presented at the beginning of the paper (Table 1), the surgeon notes an undesirable situation—poor drainage from the heart that is causing it to distend. While he searches for a coronary artery on which to graft a bypass vessel (which involves communication with the PA and scrub) the surgeon simultaneously communicates with the perfusionist to try to determine what is causing the undesirable situation. At the end of the problem-solving segment, he tests a possible cause (leaking aortic cross-clamp) and solution (adjest the cross-clamp). Finally, he explains what he thinks was wrong (the cross-clamp must have been leaking…).

5. Discussion

Teams working in high-complexity and high-impact settings ensure safe and effective outcomes through coordinating actions that serve shared goals. Distributed cognition provides a framework that enables us to understand the roles of information processing by and between actors,
their tools, and their environment, within an activity system. Cognitive ethnography is a methodology providing empirical means for revealing the mechanisms underlying regular production of coordination by highlighting how information flows through the activity system in support of task work. For a given activity system, a state of coordination is situated in sequential time and task space. A hypothesis of this research is that mechanisms promoting or providing coordination serve to control the system by providing means for modulating and making predictable the system’s transitions through task state space.

5.1. Situation awareness of an activity system

It is commonly understood that “situation awareness” (SA) is a critical feature of effective human performance in complex tasks. In the human factors literature, four epistemic properties are taken by researchers to underlie SA: (1) the perception of relevant facts, (2) comprehension of those facts for the current situation, (3) projection forward to possible future situations, and (4) prediction of future situations given expected external influences [12–14]. Human factors research in anesthesiology and surgery has contributed to this formulation of SA [15,16]. The four epistemic requirements of SA imply a model of cognition in which SA is achieved through properties of individuals: agents perceive facts and, through mental manipulation of these facts, comprehend and predict future states of the environment. In our analysis of cardioplegia management, we found these epistemic states to be a natural consequence of the activity and we suggest that SA is being produced instead through behavior of the system. Instead of seeing these epistemic states deriving directly from internal workings of individual agents, our analysis shows that they depend upon the interactions organized by the activity system. The communications we have described function to: (1) directly determine the current state of the system (Direction), (2) reflect and create understandings of the current state of the system (Status, Alert, Explanation), and (3) establish expectations about future states of the system (Goal-Sharing, Problem-Solving).

This pattern of communication serves as a coordination device because it enables, through propagation of representational states through the system, the sequencing of actions to accomplish tasks required by the work. In the process, the verbal exchanges clarify the nature of the current (actual) and future (expected) system states. That is, this schema for communication is a coordination device that serves to control the behavior of this complex dynamic system. In this case, situation awareness arises out of the processes that manage information flow and action.

5.2. Limitations

Although our research investigated many aspects of heart surgery, this paper reports on a subset of the entire activity system that is organized by the particular tasks of cardioplegia management. In part, this limitation stems from our access to relevant event data on videotape. However, in order to study complex human activity in the wild, there will always be a need to find the “natural joints” in an activity system that afford a research focus. The communications between surgeon and perfusionist during cardioplegia management provided such a “natural joint” and is what we report on in this paper.

The heart room we studied is a very cohesive health care unit within the spectrum of activity systems involved in health care. As such, there appears to be greater “specialization” of constraints and resources than is typically possible in other health care activities. The heart room has a relatively stable staff, scheduled periods of work, a small number of well-rehearsed types of cases, and clearly defined functional and team roles. It would be useful to contrast different health care activity systems (e.g., a heart OR and an ICU, or even heart ORs in two different types of institutions) for the degree to which constraint and resource specialization is possible and the advantages and barriers this creates to the quality of the work.

Our analysis here did not attend to non-verbal forms of information that supported the cardioplegia management task. This limitation in our study was created not by our theoretical framework (on the contrary, the framework explicitly accommodates these contributions to distributed cognition) but by the data we were able to capture on tape that we could synchronize with the actions required of this task. For instance, the heart–lung machine digital inputs and display provided critical information supporting task work, which we were unable to capture on tape. To take one example, the cardioplegia bolus sizes were often entered into the machine, monitored by the perfusionist, and then served to “prompt” him or her in initiation of a Status exchange with the surgeon.

5.3. Related research

Others have utilized the concepts of distributed cognition in their discussion and research of health care processes and technologies [17–21]. Horsky and colleagues [20] utilize concepts of distributed cognition to analyze the user-interface of computerized physician order entry (CPOE) systems. In their work, “The distributed view of cognition represents a shift in the study of cognition from being the sole property of the individual to being ‘stretched’ across groups, material artifacts, and cultures” (p. 7). Their focus on the user-interface privileges individual clinicians in explanation of cognitive behavior related to medication ordering. In this approach, the boundary created by the individual remains an exclusive locus for understanding cognitive behavior, even while accommodating the individual’s manipulation of structures (both internal to the individual and external on the computer interface) to simplify tasks and accomplish goals.

Nemeth and colleagues [21] describe distributed cognition as “the shared awareness of goals, plans, and details
that no single individual grasps” (p. 727). Using their approach, “Cognitive artifacts...such as schedules, display boards, lists, and worksheets that are part of a distributed cognition” are symbolic objects that encode “what matters” in a domain of work practice. This suggests that artifacts constitute a prime vehicle for investigating instances of “a distributed cognition,” where investigation can occur at both the structural (organizational) level and the behavioral (individual) level. This provides useful insight into the roles of cognitive artifacts, but the connections between these levels remain unclear without positing an independent theoretical model (i.e., distributed cognition as model versus phenomenon of study) and specific units of analysis that entail artifacts as members of a broader class of resources for cognitive action.

Our own use of the framework of distributed cognition is significantly different from these two examples. Our framework of distributed cognition posits a fundamental role for artifacts, both those instantiated by material technologies (e.g., a computer interface or a perfusion machine) and those instantiated by other agents (e.g., behaviors and speech). We do not privilege individuals or the material artifacts of a workplace, but instead, we privilege action within an activity system and posit an information processing account to characterize it. Cognitive resources within our account are distributed and typically are engaged, concurrently or serially, by multiple agents in a system of organized activity. Information processing in an activity system can occur without human intervention at all, but when human agents are involved in that processing they are always contextually embedded agents (“the surgeon of a heart room team opening the patient’s chest”). The embedding activity system has time-variant configurations (arrangements of constraints and resources) that simultaneously define current task state and entail historical properties. These are the system’s organizing features; they guide action, with consequences for those inside and those outside the system.

5.4. Implications

Recent attention in the healthcare community to patient safety, medical error, and quality improvement has led to reexamination and redesign of healthcare processes. An important emphasis in these efforts has been promotion of healthcare information technologies (HIT) in clinical processes. Though there is general agreement, confirmed by published reports, that this incorporation of HIT into healthcare processes has been beneficial, there are also indications that HIT may produce unexpected and sometimes harmful results: installation of computerized order entry by physicians may facilitate medical errors [22], and in some cases possibly harm patients [23]; implementation of barcode medication administration systems can create safety hazards [24]; computerized documentation by physicians may reduce the usefulness of information in progress notes and alter existing communication practices by physically separating nurses from physicians while they perform tasks [25,26], reducing opportunities for low-bandwidth sharing of information as happens in common workspaces such as a nursing station [27]. As a result of reports such as these, the attention of the biomedical informatics community has been refocused on the intersection and interdependence of social and technical factors in HIT design and implementation, in order to maximize benefits and minimize harm.

To design and refine HIT implementation, and more importantly, to reengineer systems of care, it is essential to understand existing processes and systems first, not only to identify potential vulnerabilities but also to understand how existing processes, including latent or hitherto unrecognized practices, activities, and side effects contribute to system resilience. When these systems are altered unknowingly, it may reduce beneficial redundancies and increase vulnerability to mishaps. To this end, observational studies such as the present one are an essential means of understanding work practice in context.

Clancey argues for and provides examples of the value of naturalistic observation, which can reveal work conditions and work practice constraints that may not be foreseeable or fully understood in the controlled conditions of laboratory-based task or protocol analysis [28]. An example from his observations of field biologists and geologists is the significance of topography as a sometimes unforeseeable constraint on practice, requiring adjustments and replanning. In Clancey’s work with field scientists the context and constraints are primarily physical. In our examination of the heart room the context is multidimensional, including physical, temporal, and clinical constraints.

Roth and colleagues, in observational studies of surgical procedures, note that such field studies are an important part of the ‘discovery phase’ of scientific work, providing an important complement to controlled investigations and experiments in the laboratory: “Field observation studies are one of the tools that support this discovery phase of the scientific process by increasing the empirical grounding of hypotheses about individual and team performance in complex work settings” [29].

The importance of field studies as a complement to laboratory investigation is also reflected in the technology assessment frameworks proposed for biomedical informatics [30] and “Technology Readiness Levels” used by NASA [31]. In both of these frameworks new technologies are examined in successive stages, first in the laboratory, then in a relevant performance environment, then incorporated into a larger system of use and intended relevant performance environment. This is necessary because performance of isolated components in the laboratory cannot be relied upon to predict performance of the entire system in real-world practice.

In our view, technologies are always embedded within activity systems and must be designed to serve the organization of those systems. The framework of distributed
cognition allows us to simultaneously consider the roles of information-processing instantiated in diverse mechanisms involving diverse media within an activity system. Understanding technology in health care will require analyses that can describe the organization of the embedding activity system, and which can describe the cognitive effects created by specific technologies and practices within that organization.

6. Conclusion

We identified a set of six types of exchange between surgeon and cardiologist and found them to facilitate specific functions of this activity system, which we named: Direction, Status, Alert, Goal-sharing, Problem-solving, and Explanation. These functions enable robust system performance through (a) making the current situation clear and mutually understood, (b) making goals and envisioned future situations clear and thereby anticipated, and (c) expanding upon the activity system’s knowledge base through discovery and sharing of experience.

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