Getting the Right Tools for the Job: Distributed Planning in Cardiac Surgery

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***Abstract*—Successful cardiac surgery requires having the right tools for the job, in the right place, at the right time, even in the face of unforeseen circumstances. We describe how cognitive and material resources in the activity system of the operating room enable well-defined courses of action (through preparatory configuration) while dynamically accommodating unlikely events (through replanning). Using ethnographic data from observations and video recordings in the operating room, we describe the nature of distributed planning in a bounded activity system with defined cognitive and physical resources. We describe the role of preparatory configuration for accomplishing expected courses of action, and the role of active replanning to achieve goals in the face of unexpected circumstances or events, using a specific case study to illustrate these phenomena. We discuss these findings, and their relevance for reconsidering the concept of error, from a systems perspective.**

***Index Terms*—Distributed cognition, patient safety, planning, surgery, teamwork.**

I. INTRODUCTION

PLANS and planning behavior by health professionals are fundamental to patient safety. The Institute of Medicine's landmark report on patient safety defined error as: "the failure of a planned action to be completed as intended or the use of a wrong plan to achieve an aim" [1], [2]. Planned actions in healthcare, however, are rarely static. As in other domains of human activity, planning in healthcare is not adequately described by rule-bound execution of specifications for action. Rather, planning occurs as situated action, occurring within complex systems of human and technological interaction. It entails a high degree of negotiation, reformulation, and *ad hoc* explanations of changing intentions, actions, and circumstances [3]. To design safer healthcare systems, we must better understand how organized preparatory activities facilitate effective, expected courses of action while accommodating to real-world contingencies and unforeseen circumstances. We must also move beyond individual-level analysis (the autonomous human agent) toward a systems-level perspective on plans, errors, and safety [1]–[5]. This paper illustrates a productive framework and methodology for making that transition.

The paper considers how activities relating to the provision of surgical tools are reflected in the distribution of cognitive and physical resources in an activity system constituted by a cardiac operating room (OR). An activity system is composed of a group of human actors, their tools, and environment, organized by a particular history of goal-directed action and interaction. The OR represents a situated activity system that accomplishes many goals in its work; the provision of tools is only one process in that system. We use the theoretical framework of distributed cognition [6]–[8] to understand "distributed planning" for the provision of surgical tools. Distributed planning refers to those features of an activity system that systematically organize actions into the future.

In this paper we focus on two distinct aspects of distributed planning: preparatory configuration and active replanning. Preparatory configuration of the activity system enables "streamlined" action according to an expected sequence, but also allows for alternative paths to the intended goal. It involves a balance between: 1) arrangement of resources to constrain future activity according to an intended sequence of action and 2) ensuring that needed resources are on hand to allow for alternative sequences of action. Replanning is a dynamic reconfiguration of plans in the face of unforeseen, if not unanticipated events, using available resources to create new paths to achieve goals.

We conducted an ethnographic study of cardiac care to understand the formal and informal practices health professionals employ to ensure safe and effective care. One arm of the study addressed how system resources are configured to accomplish successful surgery and prevent adverse events, through both explicit and implicit constraints on resources and actions in a cardiac OR. In this context, we consider the activity system to be the group of actors (together with tools) that perform a case in a highly configured "heart room." Typically, the group consists of: a surgeon; an assistant (here, a physician assistant); a perfusionist; an anesthesiologist; two "scrubs" (nurses or scrub technicians) who assist within the sterile field; one nurse circulator, who assists outside the sterile field to provide supplies for the room; and one nurse manager who provides a "bridge" to the supply room and other external resources.

The resources in a single OR are limited by the constraints of time, expertise, space, and equipment. In cardiac surgery, of course, time is critical. Delays in key stages of open-heart procedures can cause irreversible damage to the heart or other body systems [9]. At first glance, planning would seem to be a resource-conserving activity, whereby more planning allows more system resources to attend to efficient execution and monitoring of surgical activities. The planning itself, however, consumes ef-

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fort and attention that, when done in real-time, can drain system resources and hinder work progress. Moreover, plans set in motion expected courses of action that can go awry if the system fails to recognize or respond appropriately to unexpected events.

A recent study of human factors and errors in cardiac surgery found that surgical teams often fail to detect and recover from commonly occurring subtle and minor errors. In isolation, these errors had little effect upon patient health outcomes, but minor errors had a multiplicative effect that produced a strong relationship to negative outcomes [10]. A better understanding of minor errors and implicit vulnerabilities could enhance patient safety in this setting.

II. METHODS

The theoretical framework of distributed cognition and the associated methodology of cognitive ethnography that we adopt here, are well suited for discovering an activity system's implicit vulnerabilities under both ordinary and stressful conditions. 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 [11]. Distributed cognition, by contrast, treats the activity system, rather than the individual, as the unit of cognitive analysis. In particular, we apply the concept of computation as the "propagation of representations" through the system to explain system behavior [6]–[8]. A representation is an information-bearing structure, such as a monitor display, a verbal utterance, or a printed label, that can play some functional role in a process within the system [6]. Processes propagate representations and produce information-bearing structures to achieve effects within the environment and, ultimately, achieve goals. An example would be an abnormal blood pressure measurement, evident in the height of a column of mercury, propagated first to an internal representation in the mind of an assistant, then to an external representation in the health record, then to an internal representation in the mind of a clinician reading the record, leading to a decision to act to correct the pressure. System behavior results from the codependent operation of these processes with the structures that they produce and structures imposed by the environment [12].

Cognitive ethnography is a methodology that prescribes observation of activity systems in action [13]. The method entails mapping how representations are propagated through the system under different circumstances and with what effect. It requires capturing specific details about work tasks, about how information gets used to solve tasks, and about how new kinds of information are produced in the process. Our methods consist of focused and general field observations in the tradition of anthropological fieldwork. Analysis aims to map the flow of information in the conduct of work and to explain the structures and processes that facilitate or inhibit the effectiveness of information flow upon clinical (and other) outcomes.

We collected video and audio recordings of 20 surgical cases involving both coronary artery bypass surgery (CABG) and heart valve replacement, using three camera angles to completely capture these events. We have spent approximately 200 h observing in the OR to learn about cardiac surgical care.[1] In addition, our work was informed by an affiliated research team conducting ethnography in the cardiac intensive care unit (CICU) where pre- and postoperative care takes place. Combined with fieldnotes based upon observations, high-fidelity video data were scrutinized to produce useful generalizations about the activity system, as well as detailed illustrations from specific cases. Two of the authors (B. Hazlehurst and C. McCullen) are cognitive and medical anthropologists (respectively) with extensive training in ethnographic methods, and the third author (P. Gorman) is an experienced academic physician with a research focus on use of information by health professionals. Our field notes reflect the process of learning "how things work" in the OR setting and provide the team a starting point for understanding the OR as an activity system. Video analysis proceeded from this baseline understanding.

We analyzed the videotape data in several steps. The first consisted of annotating the general features of each case. By viewing the most inclusive video angle (which covers most of the activity in the room at a given time), we produced "procedure maps" for each case. Procedure maps are coded timelines of observed activities that facilitate cross-case comparisons and generalizations about usual procedures. Episodes of interest were identified, with a focus on those in which features of the activity system that are usually implicit were vocalized and thereby made apparent. Through repeated viewing of cases and episodes, general patterns were identified and questions generated for clarification by participants. Further analysis used the procedure maps to generate descriptions of the system and to identify segments for detailed transcription (see Table I). In the case reported in this paper, complications arising from unfamiliar circumstances create "stress" that reveals the system's cognitive properties by making explicit the means for coordinating actions in real time.

III. RESULTS

A. Plans and the Distribution of Resources

In the OR activity system, cognitive resources and information processing are distributed. That is, agents in the system collaborate to accomplish a shared goal, with each agent possessing overlapping, but nonidentical expertise, responsibilities, inputs, and task orientations. Communicating effectively about surgical tools is complicated by the fact that the agents involved (scrubs, surgeons, and circulators) draw upon different understandings, practical experiences, and situational information to refer to the tools they are using. Fig. 1 shows the layout of the open-heart surgical room during setup or "preparatory configuration" for surgery. Once surgery starts, the room will be rearranged with the "back tables" and heart-lung machine arranged closer to the patient, effectively "boxing in" a sterile field that encompasses the patient, and providing the area where surgeon, physician assistant (PA), and scrubs work.

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[1] The human subjects aspect of this research were approved and overseen by the Institutional Review Board (IRB) of the healthcare organization where the study took place.

TABLE I
ILLUSTRATION OF VIDEO DATA ANALYSIS PROCESS

Time	**Procedure map description**	**Handwritten annotations**	**Transcript of sequences of interest showing coordination of actions**
0:13:25	Surgeon says green off, then flush cardioplegia.	S → P Direction, action, confirmation	S : Green off P : Green is off. S : Flush cardioplegia. P : Flushing S : Off P : Off
0:13:45	Surgeon asks for cross-clamp. Then says flow way way down. Then clemp is on, up on plege. Perf confirms all these steps.	1. Vent off 2. Flush plege 3. Cross clamping (flow down, clamp on, plege up) 4. Arrest	*The surgeon asks for and receives the aortic cross-clamp from a scrub nurse* S : Flow way down. P : Way down, sir. S : Clamp is on. Up on your plege. P : OK, flow's back up. Plege is coming.
0:14:15	S1 asks for new gloves. Surg says heart is fibrillating. Surgeon placing cold ice slush on heart. Tells perf they have a nice arrest.	S → P Report system status	S : Fibrillating. P : Thank you. S : We have a nice arrest. P : Thank you (…)

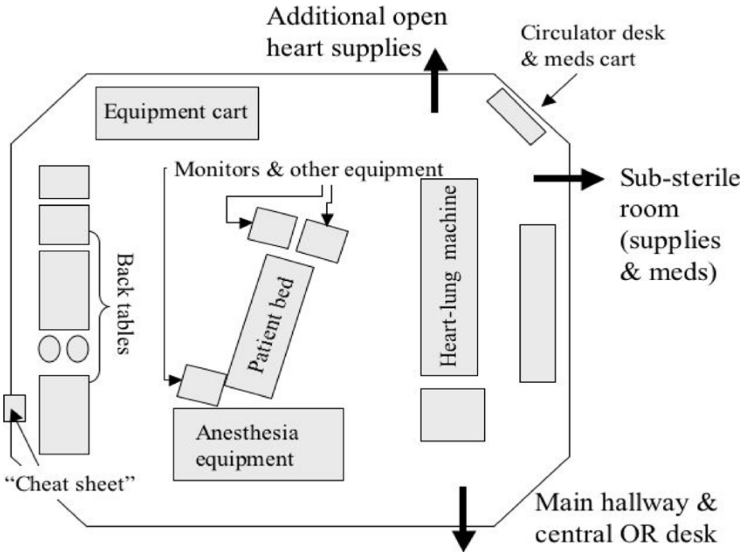

Fig. 1. OR during preparatory configuration.

Once the case is under way, routine requests for tools are generally organized to conserve the surgeon's attentional resources so that he can attend to many concerns of the case. These include: collaborating with the PA and scrubs to perform manipulations of the heart; collaborating with the anesthesiologist to monitor and manage hemodynamic status; coordinating the cardiopulmonary bypass process with the perfusionist; informing the entire OR team about certain key stages in the procedure; requesting changes in settings on various machines; and requesting tools from scrubs. Such tasks require the surgeon to exchange information, collaborate on decisions, and communicate needs and expectations to the other OR team members.

The team knows the surgeon's preferences, has expectations about what will be needed based on repeated performance of tasks, and arranges tools accordingly during setup. Thus, the surgeon frequently has only to hold out his hand in order to receive the correct instrument. In the simplest case, verification that the request was understood correctly is implicit in receipt of the appropriate tool. It is common to hear surgeons use abbreviated terms for the tools they request (e.g., asking for "the saw" instead of specifying the type of saw and the orientation of its blade). These abbreviated, even nonverbal requests are sufficient and effective because the team has prior knowledge and experience with the task and the tools required. Thus, the OR activity system is organized to minimize the surgeon's resources in *requesting* tools in routine situations.

Other actors and artifacts within the system embody resources for tool *provision*. Most demands for tool provision in routine situations fall upon the scrubs. Scrubs' activities are organized around elaborate setup work (preparatory configuration), employing various cognitive artifacts [14], such as "cheat sheets" (see below), inventory lists, and a standardized layout of tools. Ideally, once surgery begins, scrubs will infrequently need to request items that are not already present in the sterile surgical field.

These preparations enable the case to follow an expected course of action, but what happens in situations of increasing uncertainty? These situations may range from common and highly scripted decision points (such as choosing the appropriate prosthetic valve based on findings at the time of surgery), to rare, unexpected, and undesirable events (such as reopening the chest during the late stages of the procedure). As uncertainty increases due to progression from expected to unexpected variability, initial plans that are operationalized through preparatory configuration become less relevant. In this case, emergent coordination of actions through replanning becomes imperative. As replanning occurs, increased cognitive resources are needed because the surgeon and the team must devote greater attention and effort to develop and communicate plans and resource requirements. Demands increase for real-time, explicit clarification and proliferation of plans and expectations that enable coordinated actions, and accommodating this depends upon a system configuration that includes the resources needed for effective replanning. In the following section, we present a general description of distributed activities that configure this activity system in anticipation of an expected course of action, i.e., the activities of preparatory configuration. This description is based on the sum total of our observations. Subsequently, we provide a detailed case of real-time situated action that illustrates replanning under conditions of uncertainty.

B. Preparatory Configuration Optimizes Resources and Minimizes Variability in Performance

Planning around surgical tools begins well before a surgery starts and continues throughout the case. Preparatory configuration of the activity system creates constraints that organize action into the future. When a case is scheduled, only the most general information is required to activate the OR to prepare for surgery. Equipment can be assembled in the room based solely upon type of case or number of bypasses intended, and the surgeon who is working the case. As set-up proceeds, staff seek additional information about expected sources of variability (e.g., the type of bypassing vessel to be used, which is typically harvested from the patient's body) as these choices are made by the surgeon or others. Staff then bring a range of possibly needed supplies to the room. Ninety minutes before a case starts, staff begin to open and arrange equipment in a standard fashion. Many tools required for surgery are packaged together in trays or packets and must be disassembled and rearranged on sterile "back tables" before the procedure starts. Staff must balance the desirability of greater availability of tools and supplies which may be needed with the cost in dollars, in space, and in complexity of preparing what may not be needed. The scrubs are primarily responsible for configuring surgical instruments and supplies, receiving assistance from the circulator, nurse manager, and others.

Cheat sheets have been designed and are managed by the lead nurses of the team to specify the equipment preferences of each surgeon for a given type or stage of procedure. They are printed out, annotated, and placed on the wall where setup takes place. They enable OR staff to translate general inventory lists into arrays of tools organized for use across time in a specific case with a specific surgical team. The layout of tools, in turn, becomes a rich representation of practice that greatly simplifies the cognitive demands of tool provision during surgery; it is also a public resource for learning the tasks scrubs are responsible for executing. Cheat sheets and standardized layout represent formal resources that help scrubs anticipate surgeons' needs, although a given procedure may deviate from usual practice in many ways. Several informal practices supplement this activity. It is common to hear conversations among staff debating how often surgeon X uses a given tool or telling a story about failure to anticipate something that was needed for a procedure. These conversations educate team members about changes in local practice and recent events. For groups who work in shifting assemblages over time, such conversations function as long-term planning activities to reproduce the system over time.

Once the surgery starts, any equipment not already in the sterile field must be obtained from a circulator. Preparatory configuration consumes resources in advance in order to minimize resource use and delays during surgery to supply correct instruments to the surgical field. When demands for unanticipated equipment needs rise, the nurse manager or an extra circulator often provides assistance to the primary circulator.

Many tools are easily discernible, even when unlabeled in the sterile field, based on their size and shape. Other tools become difficult or impossible to identify when they are provided for use (i.e., medications or small items like sutures or needles that are removed from packaging for placement in the sterile field). This presents vulnerability to error. System configuration regarding the use of such tools can include special procedures to increase the likelihood that the right tool is provided in the sterile field. In the case of medications, various formal procedures to ensure proper identification and placement include verbal and visual verification when medications are drawn from original packaging, labeling of all medication containers (syringes, pitchers, etc.), and double-checking procedures. In the case of sutures and small instruments, some sterile labeling is often left on the item until it is presented to the surgeon for use. As we shall see, however, this labeling may have insufficient or ambiguous information.

Effective requests for tools during the procedure can be highly specific or ambiguous. For example, a surgeon might ask if there is a "longer" instrument available, or he might ask to see "what else" the scrubs have available for a certain task. Ambiguous requests that are based on situational and shared understandings can be highly efficient, as when a surgeon makes a hand signal to indicate the type of tool he wants or simply holds his hand out because he can expect the scrub to anticipate the next tool he needs in a routine task. Thus, it would be a mistake to conclude that highly descriptive requests are always better than ambiguous requests for tools. In fact, system configuration and expected practices usually constrain the OR system in a way that sparse and even ambiguous communications result in safe and efficient actions involving the provision and use of surgical tools. Preparatory configuration is aimed at ensuring correct propagation of expectations for tool use during a given case and across time.

Three important features of the activity system limit the role of preparatory configuration in charting out the future course of actions for the system. First, an overarching stance toward planning in the cardiac OR system includes a "crisis" mentality that motivates actors to prepare for catastrophes. Even though preparing for the unexpected takes a great deal of work, this feature of the system justifies the consumption of significant system resources toward "planning to be surprised" [15]. Second, there is a related need to accommodate spontaneous replanning that occurs once preparations and plans have been put in place. Such replanning can become very resource intensive, especially if configuration has "over-constrained" the system so that it cannot easily change its course. Replanning occurs frequently, and can arise in response to variability in the patient's state, the progression of the surgery, etc. When such replanning activities entail responses to life-threatening situations, they are likely to have been accommodated in preparations for crises. Most instances of replanning, however, entail seemingly minor changes in plans. They represent a domain of system activity that could generate the "minor errors" that cardiac OR teams are unlikely to detect and repair [3]. Third, "novelty" introduced by new technology, new technique, new staff, and new policy and regulation limit the role of preparatory configuration to dictate a specific course of action. We now turn to an example of situated activity that represents a noncritical instance of the replanning process under conditions of uncertainty.

C. Replanning Under Uncertainty

In this case, the surgical team was operating on a patient who had undergone CABG surgery in the past. At least three things made this case slightly unusual: the reoperation, the use of the radial artery as the grafting vessel, and the use of a new technology. The ethnographer was told during set-up for this surgery that "re-do" operations are always unpredictable. "You never know what you will find," one scrub nurse said. In large part, this stems from disruption of normal, fairly predictable anatomy by the first surgery and subsequent healing. The surgeon decided to use a radial artery (from the forearm) to create a bypass graft. In most cases, the bypass graft is either a left internal mammary artery (from the chest) or a saphenous vein (from the leg). Bypass grafts are vessels that have proximal and distal anastamoses (connections). The proximal is "upstream" relative to the blood flow, and occurs at the aorta, which pumps oxygen-rich blood out of the heart's left ventricle. The distal, "downstream" anastamosis, delivers oxygen-rich blood to the coronary artery, at a site past where the coronary artery is blocked. Thus, the graft vessel "bypasses" blockages that impede the supply of oxygenated blood to heart muscle.

1) Replan1: Using Spring Clips for Proximal and Distal Anastamoses: After going on bypass at about 2:30 pm, the surgeon announces a change in plans. He wants to use spring clips (a relatively new technology) to connect the bypass vessel both proximally (to the aorta) and distally (to the coronary artery). The first scrub (S1) confirms that the surgeon wants to use the spring clips for both anastamoses, then relays this request to a circulating nurse. There happen to be two circulators in the room at this time. S1's first request is to the more experienced one (C1), who also works as a scrub in the heart room. When S1 realizes that C1 is not available, S1 asks a less experienced circulator (C2) for spring clips "for doing the proximal and distal." These clips are kept in a supply area right outside the OR. Together, S1 and S2 point to where the clips are kept. S1 adds, "You should have two different types." C2 leaves the room. Then, as if to check that his instructions were correct, S1 says to C1, "You know what I'm talking about… should we have both out here?"[2]

While C2 is away getting the requested spring clips, the surgery work proceeds. C2 comes back from the supply area and asks what size clips they want. S1 replies, "I'm gonna need both sizes, for the proximal…" He leaves the sentence unfinished and turns to the surgeon for clarification, "You want both or you want one size? The surgeon replies: "No, I'll use the little mammary distals and (obviously) the… " Before the surgeon is finished, S1 replies "—the regular (…) clips?" S1 relays to C2: "So I need each size." S1 next asks the surgeon how many spring clips he will need. (The clips come in packets and it saves money to open just as many as will be needed.) The surgeon's attention now turns to the next task, examining the radial artery that was harvested from the patient's arm by the PA earlier.

We see the surgeon changing his mind about the material he will use to connect the grafts to the aorta (proximally) and the coronary artery (distally). This change in plans occurs once the case is underway, negating preparations for provision of anastamosis tools that occurred before and during set up. Instead of sutures (akin to thread), he decides to use spring clips, a novel device used for grafts. Spring clips are self-closing, devices that are used in place of sutures. Stated advantages include more rapid application and better seal of the anastamosis. They are a relatively new technology, not in routine use at present.

At this point, more than the usual resources have already been allocated toward requesting and providing a tool. S1 needs to clarify the surgeon's request, provide detailed information to the circulator about the location of the items, and double-check that the request has been interpreted correctly by asking other experienced team members who work in both the circulator and scrub roles (S2, C1). None of these activities routinely occur in requests for tools to circulators once a case is underway. This unusual expenditure of resources is likely the result of the novelty of the spring clips and ambiguities in the terminology used to describe them. Both factors create challenges in coordinating understandings and expectations across the system.

As Table II shows, many terms can be used to specify both the type of clips and the site of anastamosis. By referring to the "little mammary distals," the surgeon indicates that he wants the smaller arterial, not the larger vein-sized distal clips. He likens the radial artery to the internal mammary artery (a more common vessel utilized in CABG procedures but distinct from a third type of vessel, the sapheonous vein that is typically harvested from the patient's leg). S1 indicates his knowledge that they will be using the "regular" (or usual) proximal clips.

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[2] Dashes show interrupted or overlapping talk. Brackets contain commentary that was not part of the verbal data. Parenthesis mark hard to hear words. Ellipses show omitted talk. Ellipses in parentheses (…) show inaudible talk.

TABLE II
TERMS USED TO IDENTIFY SPRING CLIPS

Vessel type	Anastomosis		Clip size	Needle size
	Type	Site	(Bigger # → Bigger size)	
Artery	Distal	Coronary artery	18	65
Vein	Distal	Coronary artery	20	65
Either	Proximal	Aorta	25	95

2) Clarifying Replan1 and Creating Replan2: In the following section, agents work to ensure correct coordination of understandings and artifacts. This involves linking tool identifiers with agents' cognitive models of spring clips and Replan1. When a new agent, who was not present during the original request for spring clips, enters the system, S1's efforts to confirm Replan1 result in Replan2. Replan2 is (mistakenly) taken to be a clarification, not a modification, of Replan1.

At 2:39 pm, S1 has received packets of spring clips in two different sizes from one of the circulators. He has size 18 and size 20 clips. It seems that the circulator interpreted opening "each size" or "both sizes," as opening vein and mammary-sized distal clips, not as opening proximal and the appropriate distal-sized clips. Holding the various packs of spring clips up, S1 cannot distinguish between them. (Clip size refers to the size of the coil that they create. Size 18 clips make a coil of 0.018" or 0.45 mm in diameter.) Now that the clips are out of the box, some of their labeling information has been removed. S1 has the clip size number only available to him.

S1 and the circulator engage in an exchange to determine which clip is bigger. At the same time, other agents in the activity system are conversing about separate issues. S1 calls to C1 and C2, asking: "Is 18 the small ones?" But a third circulator (C3), who was not present for the initial request for spring clips, is now in the room. S1 asks her, "Which are the small ones on there, [C3] … S-20s or S-18s?" C3 was not part of the earlier conversation about using both distal and proximal clips, and thus might easily assume that S1 wanted to determine which of two distal clips is smallest. C3 responds: "I don't know. Are the 18's the smaller ones?" C3 checks the label of the box that holds the clips and replies, "the mammary ones are 18." S1 explains that the packaging he has in the sterile field doesn't say mammary or artery on it, just clip size.

After discussing how many clips of each size were provided, S1 and C3 re-confirm with each other the difference between the types of clips.

S1: *So the twenties are the big ones? Yeah, sure, I'll remember that.*

C3: *We're using the twenties for –*

S1: *– The ao[rta] –*

C3: *– Big ones for the proximal. The little –*

S1: *– The little ones for the distal… yeah.*

C3: *Alright.*

S1 and C3 have mistaken the relevant information provided to them in Replan1, in large part because the context that grounds their clarification effort has shifted. The correct, larger, clips (proximal/aortic/size 25) are not in their field of attention. S1 is not aware that the two sizes of clips he has are *both* distal clips, and C3 is not aware that a third type of clip—bigger than either two she is comparing—is relevant to this conversation (the proximal aortic clip). In this case, replanning has led to mistaken understandings and incorrect tool-provisioning. Despite overt attempts to *avoid* miscommunication, ambiguities in the representation of information and the team's lack of familiarity with the tool contribute to the wrong tool being provided. Participants' cognitive models do not correspond, and the terms used to refer to the clips in Replan2 do not clarify the situation.

3) Error Detection and Formation of Replan3: The proximal anastamosis follows the distal. At this point, the surgeon notices that he did not receive the clips he intended to use. When he started to use these clips for the proximal graft, he apparently detected the discrepancy, in part because the needle used to place proximal-size clips into the aorta is noticeably different. The following section shows how one component of the activity system (the surgeon) recognizes an error not detected by other components of the system (S1 and circulators). This detection is likely afforded by differences in: 1) visual media that hold representational structure used to identify the spring clips; 2) mental models used by actors which constrain the interpretations made of the available information; and 3) tactile/kinesthetic information that inform the surgeon's perception of the clip. Only the surgeon wears magnifying loupes to perform the procedure, and he alone actually uses the clips and so is in a position to detect differences in application. In this sequence of events, identifying terms in utterances and labels do not resolve misunderstandings about the clips and their use. However, visual and tactile media unavailable to S1 and circulators are available to the surgeon, who detects the discrepancy and corrects the propagation of mistaken understandings.

Just before 3:00 pm, the distal anastamosis is finished. After a short interruption, the surgeon starts to work on the proximal anastamosis. At 3:04, he looks up from the patient's chest. He looks at the used clips laid out on patient's abdomen, and recognizes that the he may be using the wrong clips.

Surg: *"[S1], these are the proximal clips, aren't they? The 5–0?*

The surgeon stops his work in the chest, folds his arms, and waits for a response.

S1: *[After a pause] So is it backward? … Can I see those boxes please? Of the different sizes? Cause this is what they gave me, the 20 and the 18, did (we) do it backward, then?*

Surg: *Well, it's a different needle. It looks like a 5–0 prolene needle. It's a big one. [The surgeon refers to the size of the clip's needle by associating it with the kind of suture it is usually attached to].*

S2: *Really?*

Surg: *I just noticed that… it's much easier to work with…*

S1: *Can you pull out that one and see what the number on that one is?" [pause as boxes are pulled out] … Oh, you know something?*

C3: *What?*

S1: *OK. I see what they did –*

C2: *What?*

Surg: *It's a big –*

S1: *– It's a totally different clip.*

Surg: *– It's a bigger needle.*

After a brief discussion, the surgeon tells the team that he has revised the plan of action.

Surg: *You know what, [S1], actually, we're sewing artery, actually, so maybe this is better. Let's just keep on going.*

S1: *OK, but the 20 they say is for vein –*

Surg: *– Yeah, you're right…but it's not a vein, it's a radial artery*

The surgeon continues talking to S1 and then to the PA as he returns to working in the chest. S1 starts problem solving to determine what went wrong. He asks C3 if there are any other sizes of clips on her supply stand. Simultaneously, the surgeon explains his reasoning while resuming his work on the proximal anastamosis.

Surg: *… I was thinking to myself, this isn't a true proximal clip. This is an actual (…) proximal anastamosis…*

S1: *Because this would be like a vein –*

Surg: *– Yeah –*

S1: *– so maybe it is right?*

Surg: *Usually the proximal is a vein. See, this is the same as the mammary clip…*

The scrub's actions suggest that he first thinks they have failed to execute Replan2. Then, he correctly realizes that Replan2 was itself a mistaken interpretation of Replan1. Completing the procedure has a higher priority than correcting misunderstandings, and the surgeon is able to formulate a new plan of action without needing to fully clarify the mistaken understandings to all agents in the system. The organization of distributed information processing in the OR allows some agents (in this case the surgeon) to replan and direct activity even when the system's understanding of the activity is incomplete or contradictory.

Different agents in the OR activity system react to these unexpected events in different ways. A two-part response to the unexpected occurs: devoting attention to understanding the error versus reforming plans based on immediately available and satisfactory resources and expectations for outcomes. The surgeon's attention shifts quickly from exploring the discrepancy to replanning the procedure. The first scrub focuses on determining the error's cause and educating others about the error.

While S1 and C3 try to determine what happened and whether there is a different clip that they never placed in the sterile field, the surgeon has to wait for S1's attention. S2 notices this and tells S1 that the surgeon is ready for the next clip. The surgeon restates that a proximal clip looks like a 5–0 prolene needle. At the same time, C3 finds an unopened box of aortic clips:

C3: *Oh, you know what? [looking at boxes on her cart]*

C3: *This has a different number –*

S1: *– OK, let's see that one, that one there –*

C3: *– than the other one does.*

S1: *What's this one here, that one under…*

C3: *Well, we haven't been using that one, but those are…. Aortic (…) anastamosis –*

S1: *– That's the one I want, right there.*

Surg: *That's the one. But we're OK. Don't open it. We don't need it.*

C3: *Alright.*

S1: *[To surgeon] Sorry about that.*

Surg: *That's alright. I think these are probably OK. Now that I'm thinking about it. It's (not gonna help) cause it's an artery…*

C3: *It says aortic… anatomic… yeah, aortic. [The handwriting on the box is hard to read]*

S1: *Yeah, that's what we would have used. One of those, and then, probably would have used 8 – the S-18's for the mammary.*

IV. DISCUSSION

We have applied the theoretical framework of distributed cognition and the method of cognitive ethnography to understand dynamic, distributed planning within the activity system of a cardiac surgery unit. We describe two aspects of planning: 1) *preparatory configuration* through which resources are configured in a manner that constrains the system to facilitate an expected sequence of actions, while providing resources that allow for alternative courses of action (what might be called fallback plans or latent plans) and 2) *dynamic replanning*, which responds to unforeseen circumstances and events by reconfiguring resources and actions to devise alternate means of achieving goals.

Setup activities that are a routine part of preparing for an open-heart case constitute *preparatory configuration* of this activity system. These activities, which begin hours before the official start of the surgery, bring into coordination a vast array of resources in routine manner. This effectively minimizes the effort in, and enhances the likelihood of, successfully attaining the goals for the surgery. As such, we take the setup activities (and the results of those activities) to constitute cognitive properties of this activity system. Importantly, these setup activities employ many resources that are external to any individual yet play cognitive roles for the activity system. Example resources mentioned above (some internal to actors, others external) include: 1) cheat sheets that detail surgeon preferences; 2) stipulations (enforced by the hospital) about which supplies can be opened and prepared prior to a surgeon requesting them; 3) conventions, habit, and regulations that dictate or provide methods of identifying and labeling items; and 4) specific information about the case at hand that will be informally passed around by the nurse manager as it becomes known. In addition, the joint activity of setup (undertaken exclusively by the scrubs and circulators) creates important learnings that facilitate the reproduction of this activity system through time. In sum, preparatory configuration creates a specific physical organization of tools and supplies while ensuring functional propagation of understandings about tools both during a case and across cases.

The case presented in the paper illustrates how *replanning* involves processes that propagate representational states through the system in order to accomplish tasks and achieve goals. Demands placed by new technologies, new techniques, or emerging issues presented by the case at hand can generate situations that are not expected, and possibly not anticipated, requiring a new course of action. In these situations, extensive effort is employed to secure the needed tools in a timely fashion. Replanning processes serve to clarify current and intended states of the system, and put new courses of action into production. While these situations undoubtedly increase the potential for mishap, replanning can proceed satisfactorily even in situations of uncertainty and miscommunication. The replanning creates coordination challenges in the case reviewed above, yet even when one component of the system fails, successful surgery results, yielding resilience in the system. The case also illustrates how resources distributed across the activity system enable replanning while dynamically balancing the demands that replanning places on other ongoing and important activities of the system.

A number of properties of the activity system we describe appear to contribute to system resilience, meaning a capacity of the system to tolerate deviations from optimal conditions without resulting in failure [16]. These include *redundancy in processes and processors*: redundancy of agents' attention and expertise, with two or more agents sharing role and task responsibilities so that one backs up the other when cognitive demands are high; and *redundancy of plans*, with "fallback" or latent plans in place to deal with contingencies and crises. Finally, the system contains *redundant resources for creation of novel plans* and reconfiguration to accomplish goals.

Vulnerabilities evident from this analysis include novelty or lack of familiarity. In the case presented: 1) the case is a "re-do" of a CABG, where "you never know what you will find;" 2) the radial artery technique is less familiar than the usual mammary artery or vein graft; 3) the spring clips are an unfamiliar, relatively new technology; 4) one circulator is less experienced and a change in circulating staff during the middle of the discussion may have created some confusion or precluded an opportunity for correction; and 5) the terms (verbal and written on labels) that identify the spring clips and their intended use are confusing. The novelty of this situation sets up a mismatch of understandings about the spring clips, their identifying terms, and their use, and creates confusion. Communicating needs, plans, and replans requires much more time and attention in this case than it does in routine situations, however, the activity system successfully navigates this complexity.

The social context of action is also noteworthy in this case. Detecting and responding to error are social and moral as well as cognitive tasks. Scrub nurse 1 allocates substantial time and attention to determining what went wrong, in part for the case at hand, in part for future learning, but also likely in part because of the potential threat to professionalism and reputation, and the personal nature of health work.

Finally, it is important to note that the case we present uses brief excerpts drawn from hours of surgery performed by a team with years of experience. Such excerpts provide a very limited view, and can seem more chaotic than is actually the case. Close working relationships, shared experience and expertise, and the technical nature of the work allow effective communication with minimal, fragmented verbalizations. Even interactions that illustrate miscommunication likely seem more chaotic to outsiders (readers) than they to the actors involved (the OR team).

What can we learn about plans and errors from an analysis provided by the framework of distributed cognition? We believe that important insights emerge due to three related features of the framework: 1) explicit treatment of the activity system as unit of analysis; 2) explicit treatment of the distributed resources that shape events through influence upon action, and 3) the empirical search for constraints which serve to coordinate actions (and goal attainment) through controlling the propagation of representational state through the system.

One prominent lesson that emerges, with ties to all three of these features of distributed cognition, is the need to reconsider the accepted definition of error. If it is true that replanning is a key contributor to system resilience and patient safety in this environment, then discarding an intended plan of action must sometimes be (and perhaps is often) desirable. But according to the widely accepted definition of error as "the failure of a planned action to be completed as intended" [1], [2], this would amount to an error. At the level of individual actors of the system, deviation from planned action may be viewed as an error. However, from the perspective of the activity system, following the original plan would be an error if replanning is needed to adjust to unforeseen or uncertain circumstances. Furthermore, with the standard treatment of plans as explicit rules for achieving intended outcomes, the important yet subtle safety-enhancing activities provided by preparatory configuration may get overlooked. In other words, close adherence to the standard treatment of error may both mislead as to how things typically go wrong and obscure insight into how they go right.

Disagreement that arises when experts are asked to make judgments about whether error has occurred in cases like the one reported here may in part be attributable to a confusion over the unit of analysis. In the case reported here, one could point to several individuals who made "errors." However, attributing the error to individual behavior greatly limits the possible preventive steps that can be taken to improve system safety in the future, and therefore fails to shed light upon the general matter. For example, one could conclude that confusion resulted from the circulator lacking the knowledge or training to provide the correct tool. Such a conclusion misses the important role that confusing equipment identifiers played in this case, not to mention the processes that detected and addresses the error in this and similar situations. It also ignores the significance of staffing patterns that create distributions of information resources (for both good and bad) in the case at hand. Further, continually changing inventories of equipment and procedural techniques (changes sometimes prescribed for patient safety reasons) create a predictable vulnerability that needs to be *accommodated and anticipated* by a surgical activity system. In sum, an individual-level analysis would result in a very different list of strengths and vulnerabilities than those we listed above.

The two levels of analysis (individual and system) for understanding safety and error are not mutually exclusive. In fact, both are probably necessary to fully understand how errors occur and how they should be addressed. However, the conceptual tools that are often used to understand phenomena at one level (say, the individual) do not necessarily translate well in the other (say, the system). When humans fail, we call it error, but when systems fail, we call it something else. A system can fail, but can it err? Moreover, can tools, machines, and technologies err? Do we ultimately attribute error to the human designers and users of these tools instead? In the case reported in this paper, we might say that one or several individuals made an error, but does it make sense to say that the labels made an error?

Taking a systems view on safety is not a new concept, yet we continue to discuss failure in terms of human error rather than system failure because we lack the conceptual tools for treating the individuals as actors within a system that performs cognitive functions. Attribution of error seems to involve underlying assumptions or beliefs about intention and motivation, which humans have but systems cannot. In our common language of description, the perceived essential nature of, respectively, "error" and "individual agent" appear to mutually reinforce each. However, one path toward greater clarity is to adopt a theoretical framework that can accommodate both individual and system-level phenomena in its language of description. Distributed cognition is a systems approach that focuses on cognition and situated interaction to explain behavior at both the individual actor and system levels. As such, we believe that distributed cognition provides a productive framework for advancing understanding of how error occurs and how it can be reduced in complex work practices.

V. CONCLUSION

This paper addresses how activities relating to the provision of surgical tools are reflected in the distribution of cognitive and physical resources in an activity system constituted by a cardiac surgery team and their work environment. We use the theoretical framework of distributed cognition to understand distributed planning for the provision of surgical tools. Distributed planning refers to those features of an activity system that systematically organize actions into the future. We highlight two distinct aspects of distributed planning: preparatory configuration and active replanning. Preparatory configuration is accomplished in presurgery setup of tools that enables streamlined action according to an expected sequence, yet also allows for alternative paths to the intended goal. Replanning is dynamic reconfiguration of plans in the face of unforeseen events, using available resources to create new paths to achieve goals. Replanning is an essential activity for accommodating dynamic and uncertain situations. However, replanning is resource intensive and can stress the system, as demonstrated in the case reported in this paper. The theoretical framework of distributed cognition and the associated methodology of cognitive ethnography are well suited for discovering an activity system's implicit vulnerabilities and latent resilience. In particular, distributed cognition is a systems approach that focuses on cognition and situated interaction to describe and explain behavior at both the individual actor and system levels in terms of regulating the propagation of representational states to accomplish tasks and goals. Analyses that employ the framework of distributed cognition make clear the need to redefine error and the need to develop interventions that can simultaneously optimize performance at multiple levels of analysis.

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