Lowering Communication Barriers in Operating Room Technology

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Objectives: This paper examines the effects of new technology on team communication and information flow in a complex work environment, and offers design suggestions for improved team performance. **Background:** Case study of a robot-assisted cholecystectomy procedure revealed teamwork disruption and an increase in the complexity of information flow and communication in the operating room as a result of the novel technology. A controlled experiment using a between-subjects design was conducted to test the hypothesis that providing critical information in a timely and accessible manner would increase communication efficiency and reduce errors in task performance. **Methods:** Eighteen pairs of participants took part in a simulated tool-changing task in surgery under one of three communication conditions: (a) no rules, (b) scripted, or (c) automated. **Results:** Teams in the scripted and automated conditions performed significantly faster than the no-rules teams ($p < .05$). Teams in the automated condition made significantly more errors than those in the scripted condition ($p < .05$). **Conclusion:** Scripted speech can facilitate team communication and adaptation to new technology; automatic information display interfaces are not useful if the modality is incompatible with operator expectations. **Application:** Information displays and communication protocols can be designed to ease adaptation to complex operating room technology.

INTRODUCTION

Technology is often employed to enhance individual, team, or system performance; however, it also can create unexpected interactions and new forms of errors (Cook & Woods, 1996; Massimino & Sheridan, 1994). The medical field is a domain in which the use of technology is growing rapidly, with high stakes in patient outcome and health care costs. Much research is being done to improve health care delivery and management, such as introducing computerized decision-making support (Tamblyn et al., 2003), computer-assisted management for antibiotics (Evans, Pestotnik, & Classen, 1998), electronic medical records (Rose et al., 2005), and integrated command-control displays for anesthesia (Xiao, Mackenzie, Seagull, & Jaberi, 2000). However, little research has focused on the immediate impact of technology on the work environment, or its usability, before it is introduced. This has implications for how effective the technology is in enhancing performance and how well the technology is accepted by the users.

In particular, medical devices and systems for surgery are being developed and introduced into the operating room (OR) faster than the surgical team can learn to use them. Recently, several studies have shown that when new technology is introduced into the OR, the goals, tasks, and responsibilities of the surgeon and nurses change (Edmonson, Bohmer, & Pisano, 2001; Nio, Bemelman, Busch, Vrouenraets, & Gouma, 2004; Webster, 2004). For example, when a new, minimally invasive cardiac surgery system was introduced, visual cues from the patient and nonverbal communication between the surgeon and the nurses during surgery were replaced by TV monitors and verbal communication from the nurses, who became the primary information source (Edmonson et al., 2001).

Other technologies such as surgical robots, originally designed for cardiac and neurosurgical applications, are beginning to make their way into many ORs for general endoscopic surgery. Although robots have many benefits over conventional endoscopic tools, such as 3-D visualization,

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six degrees of freedom manipulation, and increased precision and accuracy, their effects on the surgical process are not well documented or understood. Observation of a robot-assisted cholecystectomy procedure provided us with the unique opportunity to witness how teamwork, information flow, and communication patterns are affected by new technology. This paper presents a case study of a robot-assisted cholecystectomy and compares its information needs with those of a conventional laparoscopic cholecystectomy procedure, followed by a controlled experiment designed to examine the effects of information structure and presentation on communication between the surgeon-nurse dyad in the OR.

The study of teamwork and team communication is not new. Research in other domains has shown that teamwork training leads to significant improvements in the quality of team behaviors and significant decreases in errors (Morey et al., 2002), especially during high-workload periods (Salas, Fowlkes, Stout, Milanovich, & Prince, 1999). To create the best teamwork attitudes and success, teams should be trained as a group, not individually (Boguslaw & Porter, 1962; Morey, Simon, Jay, & Rice, 2003; Morey et al., 2002). For a team to successfully integrate new technology into the work flow, crew communication, good teamwork skills and coordination behaviors, social support, and good leadership are important (Morey et al., 2002).

In the training of team communication, using patterns in speech and standardized communication sequences has been shown to improve team performance (Bowers, Jentsch, Salas, & Braun, 1998; Xiao, Hunter, Mackenzie, Jefferies, & Horst, 1996). Xiao et al. (1996) studied coordination of teams in emergency medical care and concluded that training in explicit communications reduced failures in team coordination. Bowers et al. (1998) conducted a study with pairs of aviators who had never before flown together and discovered that better performing teams had more consistency in their speech patterns than did poorly performing teams. Homogeneous communication patterns allowed team members to detect anomalies more quickly.

Team communication can be accomplished through modalities other than standardized language. For example, if team members are able to see what the others are doing, even from a quick glance out of the corner of their eyes, they can coordinate their actions better even while busy with other tasks (Segal, 1995). When actions are coordinated, information can also be passed between team members without visual contact, such as talking face to face. Interestingly, though, more communication does not always lead to better performance (Jentsch, Sellin-Wolters, Bowers, & Salas, 1995).

The benefits of team training and the implementation of standardized language are supported by the common ground theory, which asserts that people's communication is based upon their mutual understanding of the situation and that all communications move them toward better understanding (Bromme, 2000). Teams that train together, learning to use the same vocabulary and identifying new tasks, goals, and responsibilities, develop their common ground, their "mutual, common, or joint knowledge, beliefs, and suppositions" during training sessions (Clark, 1996b, p. 93). The concept of common ground is very similar to the concept of shared mental models in teams (Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995; Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). Several types of shared mental models can exist in teams: technology based, job/task based, team interaction based, and team based. In particular, the shared model that contains information about each teammate's knowledge, skills, attitudes, preferences, strengths, weaknesses, and so forth allows team members to interact more effectively with one another. That is, the more knowledge teammates have about one another, or the more "common ground" the teammates share, the better the team will function under changing conditions. Therefore, teams that train together, in contrast to teams composed of members who were trained separately, would likely start with a much better understanding of the technology or equipment involved, their teamwork roles, goals, and information communication needs, thereby facilitating enhanced performance and efficiency.

The goals of this research were to examine the effects of a new technology on communication between surgeons and nurses in the OR and to delineate safe practices for integrating new technology into the OR. Based on the case study of a robot-assisted cholecystectomy, a follow-up controlled experiment was conducted to examine the effectiveness of structured communication and automatic information display as alternatives to the unstructured communication of information typical in the OR.

CASE STUDY OF ROBOT-ASSISTED CHOLECYSTECTOMY

Case Description

This case study exemplifies the all-too-common practice of introducing medical devices without having conducted usability tests. The purpose of this case study was to examine the disruptions to normal communication and work flow that might result from the introduction of a robotic system into the OR. A robot-assisted cholecystectomy procedure was compared with one using the conventional laparoscopic approach.

The robotic system consisted of a control console and two teleoperated robotic arms. Because of the size of the control console, it was positioned in one corner of the OR, across the room from the operating table. Thus, the surgeon's view of the patient was obscured by the console. A monitor located on the console provided a view of the internal operative site. Seated behind the console, the surgeon used two handheld controllers to manipulate the end effectors of the robotic arms. The teleoperated robotic arms were attached to the operating table and positioned above the patient. Each robotic arm held a laparoscopic instrument that was inserted into the patient's abdomen through small incisions. The nurse was responsible for changing these instruments as needed throughout the procedure.

The same surgeon who performed the robotic procedure was observed while performing the same operation with the conventional technique, with a different nurse in each case. In the robotic case, the surgeon and nurse had been trained separately on the use of the robotic system on cadavers and animals but were working together on a human patient for the first time. Both robotic and conventional laparoscopic procedures were recorded on videotape and audiotape for analysis.

Results and Discussion

Using hierarchical task decomposition as previously employed by Cao et al. (1999), the videotaped surgical procedures were decomposed into steps, tasks, and subtasks based on task demands and requirements, according to operationally defined beginnings and endings of events. In addition, an analysis of the information flow between the surgeon and nurse was performed from the audiotape transcription.

The learning curve for the surgical team consisted of learning about the technology itself, learning a new vocabulary to communicate, and adjusting to new tasks and responsibilities, while reestablishing common ground. There were actions and decisions made with the robot that were not necessary in the conventional laparoscopic case. Critical information for the surgeon and nurse was no longer visually accessible. The surgeon and nurse were separated physically, with no direct line of sight to each other's actions or information sources, thereby necessitating verbal communication of information to coordinate their tasks. In laparoscopic surgery, for example, when a surgeon wanted a tool changed, the nurse often anticipated the need and had it ready. Then, assuming perfect execution, four subtasks were required to change tools: pull out the current one, hand it to the nurse in exchange for the new tool, take the new one, and insert it into the patient (see Figure 1a). In robotic surgery, again assuming perfect execution, this process required at least eight subtasks, with many more actions (see Figure 1b). This tool exchange, which averaged 82 s as compared with 5 s in conventional laparoscopic surgery, showed that the surgeon and nurse depended on each other for critical information, much of which was conveyed verbally.

In fact, more verbal exchanges were required in the robotic case than in the conventional laparoscopic case. Figure 2a illustrates the information needed by the surgeon in conventional laparoscopic surgery. Information about where the tools were in the body was obtained via physical/kinesthetic feedback and visual feedback from the operative site, and the status of the procedure in terms of progress was gained through general monitoring.

When a robot was added to the equation (see Figure 2b), the surgeon needed more information and had to acquire it in new ways. Much attention was devoted to communicating with the nurse and scanning the control panel to update the status of the "physical state" (e.g., whether tools were secured in the robot arm) and "control state" (e.g., whether the arm had been disabled) of the robot. As a result, the surgeon was dealing with a number of informational inputs that were not directly related to the care of the patient.

Errors in the communication of critical information were noted during the robotic procedure.

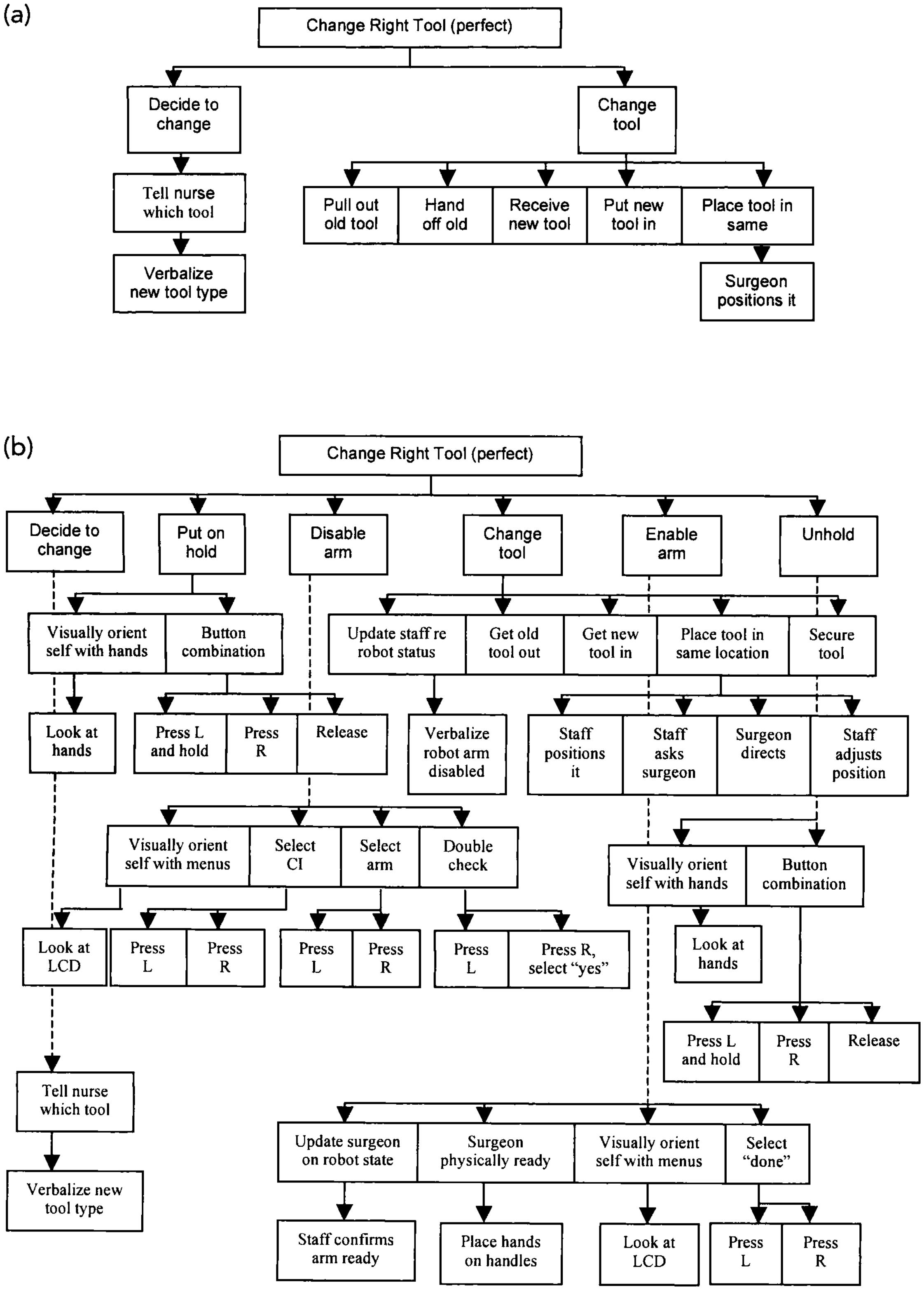

Figure 1. (a) Task decomposition for a tool change in conventional laparoscopic surgery. (b) Task decomposition for a similar tool change in robotic surgery. (CI = change instrument.)

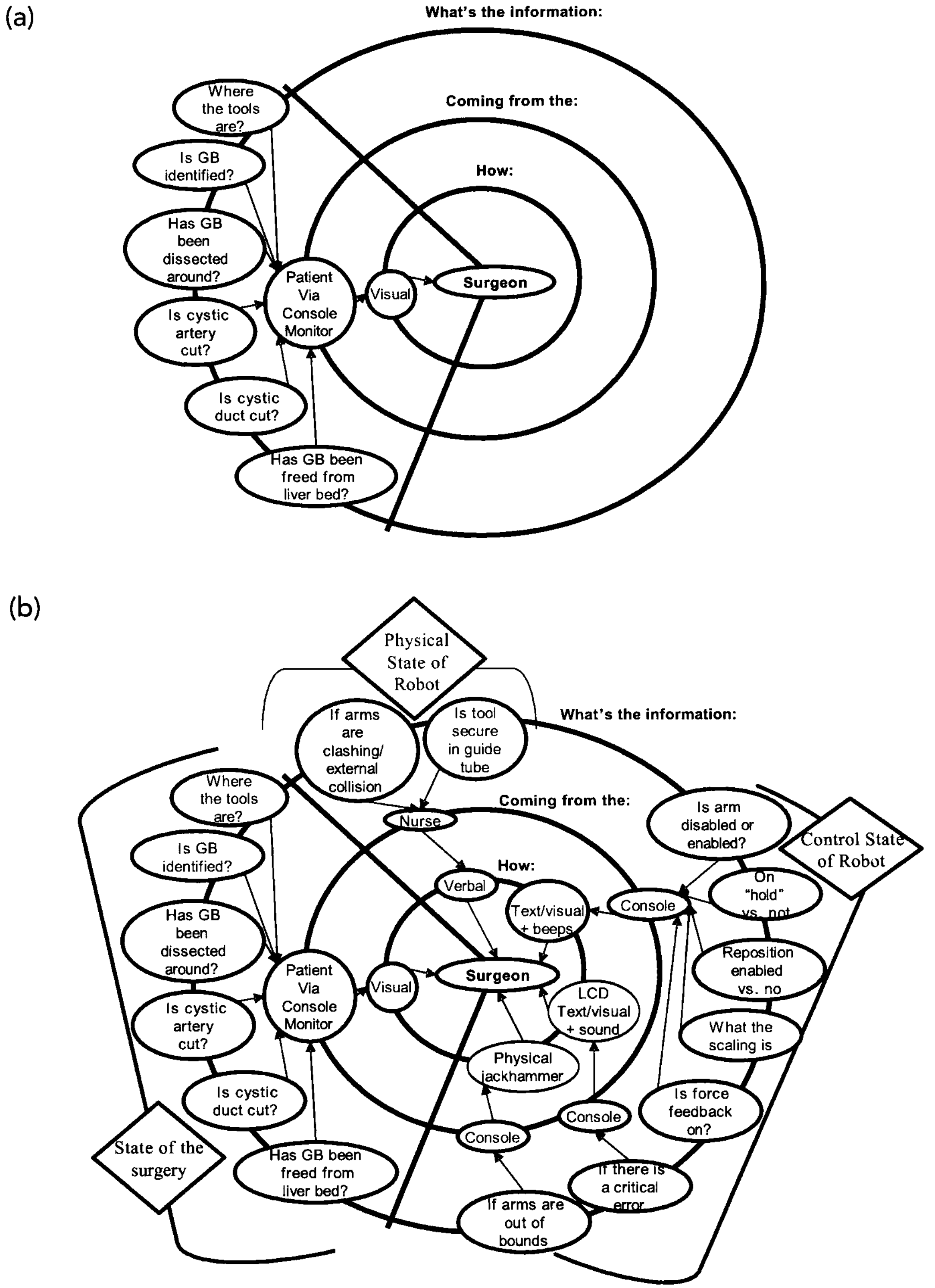

Figure 2. (a) Information flow and information required by the surgeon in laparoscopic surgery. The outer ring shows what the information is, the middle ring indicates how the surgeon receives this information, and the inner ring is the modality of information. (b) Information flow and information required by the surgeon in robotic surgery. The outer ring shows what the information is, the middle ring indicates how the surgeon receives this information, and the inner ring is the modality of the information. (GB = gall bladder.)

On at least one occasion, the surgeon enabled the arm before the tools had been secured, constituting a significant breach in patient safety. There was confusion about who should be providing feedback, and when. There were also many pauses in the information flow between the surgeon and the nurse, especially during the tool changes. For instance, when the nurse did not inform the surgeon that the new tool had been secured, both parties were idle, each waiting for the other to take action. This situation did not exist in the conventional laparoscopic case, in which the surgeon and nurse could see each other's actions.

Given the importance of communication efficiency and safety in surgery, and in particular the potential for errors while adapting to new technology, better methods for communication of information between OR team members are needed, particularly between the surgeon and nurse. Based on the case study, we surmised that individual expectation and structure or format of information can potentially affect team performance in the OR. An experiment was conducted to test the hypothesis that a prompt and structured sequence of information would result in better team performance than would unstructured and delayed feedback. The experiment employed a scripted dialogue to structure communication (Bowers et al., 1998; Xiao et al., 1996) and automatic information display to provide prompt and timely feedback to the users. Therefore, scripted dialogue was expected to yield better performance than using unstructured communication, and an automatic information display was expected to yield the best performance.

COMMUNICATION EXPERIMENT

To simulate the interaction among the surgeon, nurse, and robotic system, a scenario was created from the case study in which (a) a tool change was required, (b) time pressure existed, and (c) negative consequences resulted from miscommunication or delayed feedback. The task of changing tools was especially significant because, as shown in the observational study, it was one of the most complicated and intricate aspects of using the robot and also required much communication. Further, more errors and near misses were noted during the tool change process.

Participants. Thirty-six volunteers (12 women, 24 men), ranging from 21 to 33 years of age, were recruited from the Tufts University community. Participants had no experience with medicine, surgery, or robotic surgical systems and were not colorblind. They were randomly paired and assigned to one of three groups and to surgeon/nurse roles because actual pairings in the real world are also random. There were 10 male-female pairs, 7 male-male pairs, and one female-female pair. The male-female and male-male pairings were roughly even between groups. The experimental protocol was approved by the university's Institutional Review Board and all participants gave written informed consent.

Apparatus. A Simulab endoscopic training box (measuring 39 x 39 x 22 cm) was used to simulate the abdominal cavity of a patient. Eight sheets of paper were stacked and placed on the bottom inside the training box. On each sheet of paper was drawn a collection of 10 or 16 circles and squares (in equal numbers). A 10-mm 0° endoscope was used to project a view of the task space (paper) onto a TV monitor, which was placed in front of the surgeon at eye level but behind the nurse (see Figure 3). A 35-cm-long wooden shaft was fitted with a felt tip pen at one end to be used as the surgical tool. Eight different colored pens could be interchanged as the tool tip. A software menu system was created to simulate the control panel for the surgical robot, which allowed the participant to "disable" the arm. A digital video mixer was used to combine the images from the computer screen and the endoscope to create an automatic information display.

Task. Participants were tested in pairs; one participant acted as a surgeon and the other as a nurse. The surgeon's task was to mark each shape in the task space with the desired colored pen, using the computer program to disable the robotic arm for tool (pen) change in the same manner as observed in robot-assisted surgery. Because the focus of the experiment was on the communication and interaction between surgeon and nurse, the simulated surgical task was chosen to be very easy, requiring no special skill that would be affected by training or that would distract the participants from interacting with the nurses and the robot control interface. The nurse's task was to replace the old pen with the new one, when instructed, and properly secure the new pen to the arm in the test box. The sequence of events was mapped directly from the task analysis of the robot-assisted surgery. The surgeon had to disable the arm (i.e., put the robot on "pause") using the computer interface before

Figure 3. Participants (surgeon and nurse) could not see each other because of the physical partition between them during the experiment.

the nurse could begin; the nurse had to secure the new tip before the surgeon could continue the task. Participants were told to complete marking as many pages of shapes as possible, with the necessary tool changes, within 5 min.

Participants wore earplugs to reduce their reliance on auditory cues from the tool changing. A partition blocked the surgeon's and nurse's views of each other, simulating the physical situation during use of the robotic system in the OR. Furthermore, the nurse could not see the control panel used by the surgeon, and the surgeon could not see how the pen and tool were attached inside the test box (see Figure 3).

Experimental conditions. Three conditions were tested in a between-subjects design. In the *no-rules* condition, neither participant in the pair was given any instruction about what or when to communicate. In the *scripted* condition, participants were each given a script. The surgeon was instructed to call out the color for the next pen when ready for the change and to say "disabled" once the tool was disabled on the control panel. The nurse was instructed to say "ready" once the new pen has been secured. In the *automated* condition, participants were told that as soon as an action was completed, they both would see the feedback displayed automatically via an overlay on the TV monitor. Each team performed three trials of 5 min, in the assigned condition. The trials were recorded on videotapes and audiotapes for transcription and analysis.

Dependent measures. The dependent measures in task performance were number of tool changes, errors, and pauses in information flow. An error occurred whenever the nurse touched the tool before the tool was disabled or when the surgeon began before the tool was secured. Communication pauses were recorded when the surgeon did not report immediately when the tool was disabled and when the nurse did not report immediately when the tool was secured, resulting in idleness of both participants.

The dependent measures in verbal communication were number of total comments, surgeon comments, and nurse comments. Semantic intention of all comments were coded and categorized as follows: (a) nontask-relevant comments, (b) giving necessary information, (c) planning comments, (d) confirmation, (e) social niceties (e.g., "thank you"), and (f) other comments (i.e., comments relevant to the task but not fitting into the defined categories).

Results

All data were first checked for normality using the Kolmogorov-Smirnov test. On normal data, an ANOVA was performed using a test criterion of $p \leq .05$ for statistical significance. Nonparametric Kruskal-Wallis tests were performed on all data that were not normal. Where main effects were found, the Tukey and the Fisher-Haytar post hoc tests were used on the parametric and nonparametric data, respectively. Preplanned paired sample *t* tests were performed on all measures for each of the three pairs of conditions.

Task performance measures. The number of tool changes, errors, and pauses (and their standard errors), averaged over trials and participants, main effects, post hoc results, and *t* tests are presented in Table 1. Paired sample *t* tests showed significantly more tool changes in the automatic condition than in the no-rules condition, $t(17) = 3.58$, $p < .01$, and more in the scripted than in the no-rules condition, $t(17) = 2.73, p < .01$. There were fewer pauses in the scripted and automatic conditions than in the no-rules condition, $t(17) = 3.73, t(17) = 4.1$, $p < .01$, respectively, but more pauses, $t(17) = 2.05$, $p < .05$, and errors, $t(17) = 2.38, p < .05$, were made in the automatic condition than in the scripted condition.

Verbal communication. The number of total comments, surgeon comments, nurse comments, relevant comments, and nonrelevant comments were averaged for each tool change (see Table 2). Also, main effects, post hoc results, and *t*-test results are included in Table 2. Results showed that the no-rules condition had the largest average number of comments in all categories. Paired sample *t* tests results showed that in general, participants required fewer comments in the scripted and automatic conditions than in the no rules condition. However, the automatic condition was not better than the scripted condition in all verbal categories.

Task-relevant comments made by the surgeons and nurses (comments that gave necessary information, planning comments, confirmation, social niceties [e.g., "thank you"], and other comments) were analyzed as a function of information structure (see Table 3). Main effects, post hoc results, and *t* test results are also shown in Table 3. Results showed that scripted teams made significantly more comments that provided necessary information (21.6 ± 1.4), whereas the no-rules teams made more confirmation comments (5.8 ± 1.1) and social niceties (0.8 ± 0.3) than did the other two groups. Paired sample *t* test results showed that in general, scripted communication was different from the no-rules condition, such that a greater proportion of the communication was devoted to providing necessary information rather than engaging in planning or seeking information. The automatic condition was better than only the no-rules condition in confirmatory comments, $t(17) = 3.05$, $p < .01$, other comments, $t(17) = 2.09, p < .05$, and social comments, $t(17) = 2.20$, $p < .05$.

Requests for information were further analyzed

TABLE 1: Summary of Task Performance Measures in the Three Communication Conditions

	Avg.	*SE*	Main Effect ANOVA	Main Effect Kruskal-Wallis	Post Hoc Results	t Test *t*(*df* = 17)
				Tool Changes		
N	5.7	0.4	Yes *F*(2, 51) = 3.802, *p* = .029	—	Significantly more tool changes in S and A than in N	S > N, 2.73, *p* < .01 A > N, 3.58, *p* < .01
S	7.1	0.4				
A	7.1	0.4				
				Errors		
N	0.3	0.1	—	Yes *X*(2, 51) = 6.276, *p* = .043	Significantly more errors in A than in S	A > S, 2.38, *p* < .05
S	0.1	0.1				
A	0.7	0.3				
				Pauses Before Providing Information		
N	2.6	0.6	—	Yes *X*(2, 51)= 21.686, *p* < .001	Significantly more pauses in communication in N than in S or A	A < S, 2.05, *p* < .05 S < N, 3.73, *p* < .01 A < N, 4.1, *p* < .01
S	0.3	0.1				
A	0.0	0.0				

Note. Table depicts averages, standard error, normality, significant main effects, and post hoc results for the amount of tool changes, errors, and pauses in providing information. N = no rules, S = scripted, A = automatic.

TABLE 2: Summary of Verbal Analysis of Numbers of Comments

	Avg.	*SE*	Main Effect ANOVA	Main Effect Kruskal-Wallis	Post Hoc Results	*t* Test $t(df = 17)$
Total Comments Per Tool Change						
N	5.0	0.6	Yes $F(2, 51) = 5.15$, $p = .009$	—	Significantly more total comments per tool change in N than in S or A	S < N, 3.11, $p < .01$ A < N, 2.24, $p < .01$
S	3.4	0.1				
A	3.1	0.5				
No. of Surgeon Comments Per Tool Change						
N	2.9	0.3	—	No	—	S < N, 2.29, $p < .01$
S	2.2	0.1				
A	2.2	0.3				
No. of Nurse Comments per Tool Change						
N	2.1	0.3	Yes $F(2, 51) = 9.73$, $p < .001$	—	Significantly more nurse comments per tool change in N than in S or A	S < N, 3.6, $p < .01$ A< N, 3.23, $p < .01$
S	1.1	0.1				
A	0.9	0.2				
No. of Relevant Comments Per Tool Change						
N	4.5	0.5	Yes $F(2, 51) = 6.40$, $p = .003$	—	Significantly more relevant comments per tool change in N than in S or A	S < N, 2.92, $p < .01$ A < N, 2.83, $p < .01$
S	3.2	0.1				
A	2.7	0.4				
No. of Nonrelevant Comments Per Tool Change						
N	0.5	0.2	—	No	—	
S	0.2	0.1				
A	0.4	0.2				

Note. Table summarizes averages, standard errors, normality, significant main effects, and post hoc results of the total number of comments per tool change, the number of surgeon comments per tool change, the number of nurse comments per tool change, and the relevant and nonrelevant comments per tool change, presented as a function of the communication condition. N = no rules, S = scripted, A = automatic.

according to their timing: before information was needed and after information should have been provided (see Table 3). Results showed that significantly more requests for information were made in the no-rules condition (1.2 ± 0.4), primarily before they were needed, than in the scripted condition (0.1 ± 0.1) or the automatic condition (0.6 ± 0.2). In general, the automatic display required more information-seeking communication, $t(17) = 4.28$, $p < .01$.

Discussion

Task performance in the teams improved when critical information was provided promptly when needed, but only when it was in the expected structured format. Automatically and instantaneously displaying state information to team members (as is common with many semiautomated systems) was intended to give participants all the necessary information to complete their tasks quickly and safely. However, participants did not use this information effectively, resulting in the highest error rate among the three groups. Indeed, the nurses often did not look at the monitor, which was positioned behind them. The barrier to accessing the displayed information may have been the change in modality (auditory to visual), which required a change in locus of attention. Performance with visual information displays could potentially improve if participants were trained to attend to both visual and auditory cues, but the automatic visual informational display alone, in this setup, is clearly not a ready substitute for verbal communication.

Although teams without any structure to their communication were less efficient, the running dialogue appeared to aid in establishing common ground, which in turn allowed them to keep the errors small. In other words, without a structure to their communication, more dialogue was necessary to achieve common ground and the desired task outcome, which resulted in slower performance. They tried to be very clear and sought

TABLE 3: Summary of Verbal Analysis for the Comment Categories

	Avg.	*SE*	Main Effect ANOVA	Main Effect Kruskal-Wallis	Post Hoc Results	t Test $t(df = 17)$
Comments That Gave Necessary Information						
N	14.9	1.5	Yes $F(2, 51) = 10.157$, $p < .001$	—	S teams gave significantly more necessary information than the N or A teams	S > N, 3.91, $p < .01$ A < S, 4.28, $p < .01$
S	21.6	1.4				
A	13.2	1.3				
Planning Comments						
N	2.2	1.0	—	No	—	S < N, 1.85, $p < .05$ A > S, 1.86, $p < .05$
S	0.3	0.2				
A	1.2	0.4				
Comments of Confirmation						
N	5.8	1.1	—	Yes $X(2, 51) = 11.784$, $p = .003$	N teams made significantly more confirmations than the S or A teams	S < A, 2.48, $p < .05$ S < N, 5.50, $p < .01$ A < N, 3.05, $p < .01$
S	0.2	0.1				
A	1.6	0.5				
Social Niceties (e.g., "Thank You")						
N	0.8	0.3	—	Yes $X(2, 51) = 9.571$, $p = .008$	N teams made significantly more socially nice comments than the S teams	S < N, 2.29, $p < .05$ A < N, 2.20, $p < .05$
S	0.1	0.1				
A	0.3	0.2				
"Other" Comments						
N	1.5	0.4	—	Yes $X(2, 18) = 7.040$, $p = .030$	N teams made significantly more "other" comments than did S teams	S < N, 2.82, $p < .01$ A > N, 2.09, $p < .05$
S	0.3	0.2				
A	1.3	0.5				
Total Requests for Information						
N	1.2	0.4	—	Yes $X(2, 51) = 7.678$, $p = .022$	Significantly more requests for information in the N condition than in the S condition	S < N, 2.55, $p < .01$ A > S, 2.03, $p < .05$
S	0.1	0.1				
A	0.6	0.2				
Requests Before the Information Was Needed						
N	0.9	0.4	—	Yes $X(2, 51) = 7.523$, $p = .023$	Significantly more requests for information before it was needed in the N than the S condition	S < N, 2.52, $p < .01$ A > S, 2.47, $p < .05$
S	0.0	0.0				
A	0.5	0.2				
Requests After Information Should Have Been Given						
N	0.2	0.1	—	No	—	
S	0.1	0.1				
A	0.1	0.1				

Note. Table depicts averages, standard errors, normality, significant main effects, and post hoc results for the comment categories, presented as a function of communication condition. N = no rules, S = scripted, A = automatic.

information at significantly higher rates than did the teams with prescribed communication so as to gain the common ground already established for the others. This is not to say that the teams with structured information were not trying to be clear and cautious – rather, the situations were *already clear* to those teams, so they did not have to work as hard to establish common ground (Clark, 1996a; Clark & Schaefer, 1989; Wilkes-Gibbs & Clark, 1992). At the same time, teams with completely unstructured communication had different means of providing information, sometimes saying one thing to convey more than one meaning or simply omitting information altogether. Multiple meanings can be confusing in team communication and can negatively affect performance if members lack the common ground to understand the additional "double" meaning.

Although there were varying levels of structure to the communication, it was clear that nonrelevant conversation was kept to a minimum by all teams. This was probably a function of the controlled laboratory testing environment, where participants were focused on performing the task according to instructions from the experimenter. This is not always the case in hospital ORs. Indeed, teams without structure to their communication were significantly more liberal in their use of socially nice comments ("thank you," "great job," etc.), which made their interaction more friendly. Teams whose dialogues were prescribed did not veer from the script, remaining more direct, dry, and verbally efficient. This observation has implications for balancing social support with productivity for the surgical team in the highly social, yet critical, environment of the OR (Boguslaw & Porter, 1962; Edmonson et al., 2001; Morey et al., 2002, 2003).

Overall, the structure provided by the predefined sequences of speech and automatic information display allowed those team members to work faster and communicate more effectively than those in the unstructured condition. However, in the case of automatic information displays, this was true only if participants actually paid attention to the visual display. Therefore, the barrier to effective communication presented by the robotic system can be diminished by employing structured communication.

Limitations. The case study was informative and helped identify unforeseen problems with current robotic system integration, especially with regard to communication in the OR, but several limitations existed in the experimental study. First, the experiment did not employ real surgeons and nurses. Surgeon-nurse teams can become accustomed, over time, to working with each other in the OR (without a robot), and they might interact or communicate differently, even in the face of an unfamiliar robot, than would two random participants with no medical background who are unfamiliar with each other. Second, there was no specific selection or control for gender and role assignment, which could have affected team communication and interaction. Third, the simulated surgical task used was neither physically nor cognitively demanding, as is the case in real surgery. Therefore, the benefit of structured communication may be more pronounced in the highly stressful OR environment.

Applications. In addition to training team members to use scripted dialogues to improve communication, this research has specific applications in the design of control interfaces on surgical robotic systems and OR layout. For example, the state of the robot and the actions of the surgeon and nurse should be visible and clear to all team members at all times. This means the surgeon should be able to see what the nurse is doing through a video feed and know when it is safe to move the robot (e.g., by a red and a green light on the robotic console), and the nurse should be able to see what the surgeon is doing through a video feed and know when the surgeon has deactivated a robotic arm to ensure it is safe for a tool change. The additional video feeds would not be necessary if the control console can be positioned in the OR such that the surgeon has a direct line of sight to the patient, the nurse, and the teleoperated robotic arms. This is a difficult recommendation to implement, given the large physical size of the console and the small size of most hospital ORs. Because the surgeon and nurse are not collocated in the OR, another recommendation would be to use earphones to receive better auditory cues from each other and improve communication in the noisy OR environment. Further, as a scripted dialogue is developed, the control panel on the robotic console should mimic that scripted language used by the surgeons; wording should be as similar as possible to lessen the need for verbal mapping and to reduce cognitive loading on the surgeon and nurse.

Applications for team training exist as well. As robotic systems are designed, training sessions or workshops should be developed in parallel. These workshops should teach each team member about the other team members' roles, responsibilities, and actions. The workshops will help team members gain common ground as well as teach and reinforce the scripted dialogue, further aiding in mutual understanding and improvement of team communication. Moreover, as these training sessions are conducted, designers should be present to witness the actual usability of the system and observe team member interactions. Designers should incorporate this real-life user data in future interface and training redesigns or enhancements.

This research also has implications for robotic systems outside of medicine. Teleoperated robotic systems designed for use by team members who are not collocated should take into consideration these results when creating different interfaces or designing training programs on communication protocols. Future research should address other team communication issues, such as those that arise when responding to an emergency with new, untested technology.

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