Information Accuracy and Sampling Effort: A Field Study of Surgical Scheduling Coordination

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***Abstract*—Coordination of dynamic schedules in complex environments requires the sampling of the current status of the system being coordinated. In many such systems that include human components, the requisite status information is unavailable or unreliable. Optimal sampling theory focuses on monitoring a system's status for changes, with limited consideration of future changes or missing information. Models of sampling for coordination and scheduling must consider resolving missing or ambiguous data points. Through field-based observations, we observed that human information-seeking involving this type of sampling balances the need for specific information with the effort required to attain the information, and the accuracy of the information. This paper uses field-based observations of the coordination of operating-room suite activities to demonstrate these factors and discusses communication strategies within the operating room context, as well as implications for technology design to support such work.**

***Index Terms*—Collaborative work, human factors, sampling methods, scheduling, surgery.**

I. Introduction

COMPLEX endeavors require considerable effort toward planning. One aspect of planning to ensure success is efficient coordination. In dynamic, uncertain environments, plans must be adaptable, and the coordination system flexible enough to accommodate continually changing circumstances, which can have cascading effects on plans. These characteristics of uncertainty and dynamism are present in a number of domains in which reliability of the system is paramount, such as aircraft carriers [1], air traffic control [2], nuclear power generation [3], railway dispatch [4], and medical care [5].

In systems that are complex and dynamic such as these, the responsibility for coordinating activities from various components often falls to designated coordinators. In the case of day-of-surgery operating room (OR) management reported later in the paper, that person is the coordinating "charge nurse" (CN). While the CN is ultimately responsible for planning and facilitating smooth and efficient operation, the CN does not act alone. Rather, a more accurate representation of the OR coordination process involves different actors, including nursing, surgical and anesthesia staff within and outside the ORs, facilities workers, technicians, and others. Importantly, coordination is distributed throughout the institution, both spatially and temporally.

The essence of the CN's coordination tasks is often not the *establishment* of a workable plan or schedule. Instead, it is the *monitoring* and coordination of resources to implement a schedule, and subsequent adjustment and adaptation of the schedule to accommodate the changing needs that arise.

The need for coordination and monitoring of complex systems is widespread. Considering that the efforts to meet the demands of complex, technical work are often supported by technology, it is important to understand the ways in which coordination takes place so that technology can be designed appropriately. The domain for our exploration of complex coordination is the management of a suite of ORs. Field-study methodologies can provide insight into the complexity of such work, and allow us to contrast the nominal, designed systems and processes with the realities of the complex work environment. The richness of the environment will allow us to develop a more robust model of the ways in which the information is sought and the factors that influence the behavior.

This paper reports field observations that examine the ways that the CN monitors OR events and seeks information about the OR status. We compare the CN's information-seeking behaviors to models describing monitoring and sampling behaviors in other technical systems that monitor visual displays. Models developed to describe the most efficient ways of monitoring (or "optimal sampling theories") can provide insight into the factors that affect the monitoring process for day-of-surgery OR schedule management.

II. Monitoring and Optimal Sampling

A body of literature exists on modeling human visual sampling in monitoring and control tasks, typically associated with process and vehicle control, and with individual operators working alone. Previous research in understanding the efforts of sampling, competition for limited attentional resources, and the nature of systems to be monitored provide a starting point for understanding more complex task situations. Optimal sampling theory was developed to deal with the problem of how to monitor a continuous process, such as the status of an airplane in flight as viewed from the cockpit, or the production of electricity at a power plant as viewed from the control room. Modeling of optimal sampling behavior is generally predicated on the assumption that the stream of information being sampled is of a known or constant rate of change (bandwidth). Within this paradigm, it is possible to calculate an optimal frequency

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with which to sample (check) the indicators of the parameters being monitored. These calculations consider a number of factors related to the process being sampled.

Using displays analogous to airplane cockpit instruments, Senders, Carbonell, and others [6]–[9] developed and tested some of the first models of optimal sampling. They asserted that the optimal frequency for sampling a given cockpit display instrument would be in proportion to the likelihood that the information would change (i.e., its bandwidth). The rationale was that upon sampling a display instrument, the knowledge of that display's status was perfect. As time passed, uncertainty grew, and the uncertainty was proportional to the bandwidth of the sampled information. Specific sampling of a given display would then depend on the bandwidth of the item being sampled, as well as the importance of the information being sampled (i.e., the cost of missing a critical event or deadline brought on by a failure to monitor the information source). When the uncertainty in the monitored parameter reached a point at which there was a danger of missing a critical event (a threshold or critical deadline), the value of the parameter was re-sampled. This type of sampling behavior was modeled by a queuing model, in which the decision to sample a given item was made by selecting which parameter to sample from a "queue" of candidate items to sample. The order of the queue was determined by the priority of the items as determined by the aforementioned bandwidth and threshold considerations. These studies were validated by tracking the eye movements of pilots in the cockpit, or in laboratory analogs of a cockpit-display monitoring task [8].

Other research added a richer set of considerations to this modeling, introducing contextual factors, such as the operator's control actions input into the system, proximity to a threshold of danger, the current state of the system, and the onset of particular stage or phase of a monitored process [10], [11].

There are also models of sampling that consider the cost of attaining information in the calculations of the optimal frequency for monitoring that information. These studies were done in a context in which the sampling cost depended on the physical effort needed to sample, as measured by the physical distance of a display indicator from the current visual fixation point of the person monitoring the displays [12], [13]. The shape of the cost function for these types of considerations has been described by Sanders "functional visual field" [12] and expanded upon by incorporating factors such as proximity to other information and visual clutter [14].

A basis for "optimal sampling" models is a simplifying assumption that people function as "uncertainty reducing machines" with the sole goal of reducing the level of risk and uncertainty in the processes they monitor. The results of numerous modeling experiments support these conclusions—that scanning behavior is indeed influenced by changes in the level of uncertainty (i.e., bandwidth of monitored processes and, therefore, their information value). Researchers do not necessarily assert that people operate solely in such a way, but they do assert that the factors considered by the models do predict performance in the limited conditions simulated [9].

Visual sampling paradigms are examinations or models of predictable information-seeking based on the urgency of the need for the information sought. They describe reasonably well the behavior of an individual person monitoring a system through its displays. These models are generally simplified, and neglect issues of collaboration between information seekers/operators. The visual sampling research also was carried out in situations in which the information sources were accurate, unambiguous, and easily accessible.

In contrast, in the domain currently studied, the monitoring task confronting the workers is more complex in a number of ways: the status indicators are generally not visual displays of individual parameters; the pertinent information is not readily available; and information provided in readily available format was often inaccurate (due to dynamic changes in the system). Clearly, monitoring the OR schedule is not identical to a process-control task used in earlier experiments on optimal sampling theory. Nonetheless, this history of sampling theories provides a foundation on which models for this new domain can be established. The supervisory-control function of presiding over a continually changing OR schedule may share common elements with the more abstract laboratory tasks used to establish optimal sampling theory.

Establishing these new models requires insight into the practices of operators within this domain. Data from observations and interviews can provide such insights. Below, we report some of the findings on sampling behaviors of the CN when coordinating activities.

III. Methods

In the collaborative management of the OR activities, the CN coordinates the scheduling of the rooms and order of cases, and tracks the status of the ORs, patients, surgical cases, equipment, and medical, nursing and support staff. The coordinating CN and the coordinating charge anesthesiologist (CA), who coordinates anesthesia-care providers and helps track patient status, are the central coordinating figures in collaborative management of the multiple-room suite of ORs.

In order to examine the activities of the CN in monitoring the OR schedule, we used field-based observations combined with critical incident technique (CIT) [16], and knowledge-elicitation interviews [17]. We carried out open-ended knowledge elicitation interviews and CIT-type interviews in the field for three CNs (out of five total working regularly in that position at the institution), two anesthesia charge coordinators (out of three), as well as four surgeons (of over 20), and 12 other staff members. Through a series of probing and clarifying questions, personnel whose position impacted the OR's daily operations were asked to provide examples of instances when daily plans were successfully executed and examples of instances when plans failed. Respondents were asked to specifically note factors that influenced the success or failure. This data was then synthesized with the data obtained via observation.

Data collection in the current efforts focused on the collaborative activities surrounding management of the OR suite, information seeking, information exchange, and status monitoring needed to support the scheduling and coordination task. Observations were carried out by two observers, a registered nurse (CW) and a human factors psychologist (FJS), over a

TABLE I
EXAMPLES OF THE SOURCES OF INFORMATION USED FOR COORDINATION OF THE OR SUITE SCHEDULE, AND THEIR ACCURACY AND EASE OF ACCESS BASED ON OBSERVATIONS AND INTERVIEWS

Information Type	Information Systems and Documents	Direct Observation	Social Networks
Patient pre-operative status (on unit floor)	Calling patient's nurse provides best information, but calling requires time and interruption of workflow.	Not a prevalent method.	Asking anesthesiology in passing requires less effort, but is less accurate and not reliably available.
Patient room location (on unit floor)	Print and computer records often outdated: easy to check but often inaccurate. Phone calls to floor higher accuracy, require more effort.	Not a prevalent method. Definitive information possible but requires extreme efforts.	Often inaccurate, but easy to check. Often more current than information system.
Staff status (Anesthesia, Nursing, Technicians)	Paging is useful for key players, but not all staff members have pagers. Waiting for return pages interrupts workflow.	Looking in OR room or seeing staff in OR suite is the only definitive method, may require effort to find people.	Second hand information provides general, not specific information; easiest to attain.
Equipment status and location	Multiple phone calls often needed to track missing equipment. Requires time and effort.	Looking for something is last resort; time consuming and interruptive.	Second hand information is easy to obtain, may provide leads, but is unreliable.
Special needs (e.g. positioning, equipment)	Official documentation often incomplete. Calling or paging necessary to resolve issues, but requires effort and interruption.	Not a prevalent method.	Asking surgeon in passing is easy and effective, but not reliably available.
Pending changes	In emergency cases, paging system useful and most prevalent. Little effort required.	When possible, checking status of emergency room for pending emergencies is informative. Requires time and effort.	For non-emergency changes, key information most often provided informally, "through grapevine." Require little effort.

three-week period during which the coordination of over 40 surgical cases was observed in a six-room OR suite. Observations were carried out primarily during the 6:00AM-4:00PM work shift, which is the shift with the highest staffing levels and task load. Interviews were not limited to this shift. Observers monitored activity at the apparent hub of the information exchanges for the OR schedule—the dry-erase display board or "whiteboard"—noting activity and conversations associated with coordination and schedule management. [See [18] for expanded discussion of the role of the whiteboard in scheduling.] The data from the observations and interviews were transcribed into narrative descriptions of events. These narratives were then parsed into separable events and event-streams representing observed scenarios. There were 199 discrete event-scenarios generated from the observations, each representing an instance of the CN or other participants interacting to resolve an issue of some kind. The events observed, combined with the CIT interviews, provided a representative record of the disruptions to the normal scheduling process, and the methods used for resolving the inevitable issues that arise.

IV. RESULTS

An examination of these data revealed patterns of activity associated with the task of managing the OR schedule, and strategies for coping with complexity of collaboration between the users in this distributed system.

The "status indicators" or information content that the CN monitored were identified within the data, and included room availability, patient condition, equipment availability, etc. (See Table I, "Information type"). Disruptions affecting these components on the day of surgery were routinely observed, and usually required an alteration in the schedule and collection of additional information to reformulate a new plan of action. It is interesting to note that the "Critical Incidents" in this domain were synonymous with ordinary activities, as the CN's stated in interviews that the "normal" situation was one of "things not going as planned." Coordination of this process often drew upon input from many different team members to exchange information. This exchange of information continued as the plan changed based on input from the various components of the system.

An analysis of the exchanges observed revealed three general means for accessing information. These were: 1) information systems and documents; 2) direct observation; and 3) social networks (all described in more detail below). The generality of these three categories provides a foundation for the classification of information sources. The current list of sources should be interpreted as an initial framework and example of such sources based on field observations. However, an exhaustive enumeration of information sources and methods of obtaining information is beyond the scope of this paper. Assessing the information obtained by the CN through each means provided an illustration of information needs and disruptions to the information exchange process (Table I). The table illustrates that different sources of information are associated with different levels of accuracy and using the sources of information requires differing amounts of resource expenditure (time or effort).

A. Information Needs and Disruptions

Information use was analyzed to elucidate the information seeking and monitoring used by the CN to coordinate the OR schedule effectively (Table I). We emphasize two factors in information sampling: accuracy and ease of access. These two factors are often part of tradeoffs in obtaining the most accurate information with the least amount of effort.

The accuracy of an information source is defined by the degree to which the information reflects the reality of the situation. While it is difficult to define the precise nature of reality, there are certain known shortcomings inherent in particular methods of acquiring information or certain sources of information that make it possible to estimate the accuracy of the information, or at least the level of certainty (specificity) that can be assigned to the source.

Ease of access is a measure of exertion of resources to acquire information. It is measured through the amount of time, effort, or energy used to attain information.

The first column listed in the table, "Information Type," describes a subset of the data sought by the CN. These information types were derived from the most commonly cited incidents in the data. The remaining three columns, Information Systems, Direct Observation, and Social Networks, indicate the broad classes for sources of information used to obtain data regarding the system status. Contained in each cell are descriptions of information-seeking characteristics of the sources of information as derived from recurrent themes in the observations and interviews. The descriptions focus on the accuracy of the information attained from the given source and the accessibility and availability of that information at a given time.

Information systems and documents are the formalized representations or technologies used to communicate data. They include technology such as telephones, pagers, cordless phones, and patient monitors, as well as electronic or printed documents from both within the OR itself and the system as a whole, e.g., the preprinted OR schedule for the day. **Direct Observations** are those data points available to the CN from directly observing the activity within the surroundings of the OR. For example, the arrival of a patient to the OR can be directly observed by the CN as the orderly wheels the patient by, and this event provides information about the patient's status and location. The category **Social Networks** denotes the informal, unmediated, face-to-face collaboration distributed across the various participants in the OR coordination process of the system.

The table and the observational data it is based on illustrate that there are tradeoffs between accuracy of information and the effort needed to obtain it. This tradeoff can occur both within sources (patient status is accurate, but difficult to obtain), and between sources (equipment status may be accurate when directly observed, but requires greater effort than relying on distributed knowledge of social networking, which can be less accurate). The CN often has a number of options when seeking information, and can chose an information source that provides the requisite level of accuracy for a minimum effort. The CN weighs the costs and benefits of each source of information when choosing a method of information seeking.

For example, the first row of Table I lists "Patient pre-op status," and under the heading "Information Systems and Documents," indicates a high degree of accuracy, but a low level of ease of access to the information. In interviews, the CNs reported that when calling the patient's floor to determine patient status, talking to the patient's nurse is a gold standard for certain, but not all, types of information. Because this synchronous communication (i.e., phone call) interrupts the activities of both the CN and the nurse caring for the patient on the floor, increasing the cost of accessing that source of information, the CN would delay calling the floor nurse until definitive information was necessary. Mediated communication, such as phone calls and interactions using pagers, can have similar information value (benefit) as social networks. However, this mediated communication usually requires more effort, formality, and time, as compared to face-to-face social networking, diminishing the ease of access (increasing information-access costs).

An alternative to the high-accuracy, low-accessibility method would be a lower-accuracy method with much greater accessibility. Relying on social networks, the CN can obtain information with minimal effort from staff that is passing by the central scheduling area (the whiteboard). This can be seen in Table I in the "Patient pre-op status" row, as the entry in the "Social Networks" column. Because of the central location and public nature of the whiteboard, staff members that have relevant information about the displayed cases may spontaneously offer pertinent information. Social networks can be similar in content to phone calls or interactions using paging systems (both information systems). Phones and pagers are not opportunistic, but rather impose time and resource demands on both parties, interrupting other activities. However, in social networking the effort involved is usually lower because face-to-face contact occurs at a communal gathering place (e.g., the whiteboard) often without interrupting either party. For example, during observations, the attending anesthesiologist was walking by the schedule board and reviewed the planned cases. He then engaged the CN to say that one of the cases would most probably not be carried out today because of changes in the patient status. He also offered an opinion that a second case would be canceled soon, pending the outcome of test results. The informal information from social networks often is not definitive, and often contains speculative information. However, this non-definitive information can be extremely valuable partly because it is accessible with near-zero effort. As will be discussed later, information with low levels of accuracy can be sufficient at certain times within the scheduling process.

Some information is available from multiple sources with no accuracy-effort tradeoff. For example, determining the patient's room location requires little effort, whether one refers to scheduling documents or to social networks (the CN can ask the anesthesiologist in charge of the patient). Both information sources require similar, low levels of effort and provide equivalently accurate information, thus, there is no tradeoff on either dimension (see Table I, second row, "Patient room location"). Unfortunately, on occasion, both of these sources can be inaccurate. The often-trivial task of finding the patient for surgery can then become a difficult and time-consuming task. During observations, there was a single instance where the patient had been recently moved to a different bed, and no one in the surgical team could immediately determine the patient's new location. The anesthesiologist and the paper-based schedule were in agreement as to the original location of the patient, but the information was no longer accurate. In this case, the anesthesiologist physically tracked down the patient through direct observation, eventually determining the new bed location. This high-effort endeavor relied on direct observation, and was highly accurate. [Note that direct observation is not a prevalent method for determining patient location, as misplaced patients are, thankfully, a rare occurrence.]

V. Discussion

The process of sampling display elements in a cockpit or control room is not a perfect analogy to monitoring the scheduling of a suite of ORs. Managing a schedule is more of a supervisory task, while scheduling is centered around temporal events or deadlines to a much greater extent than classical process control. Despite these differences, there are some important concepts that these sampling models introduce.

Sampling theory deals with tracking changing system status, while the type of monitoring in the current study involves the proactive collection of data about uncertain system status, in which increasingly accurate information becomes available gradually. The coordination of ORs, thus, contrasts with the classical optimal sampling paradigm, and requires a variant on the sampling models to accommodate the differences. Based on a synthesis of the observations and the classical theories of monitoring, we propose a model of collaborative, distributed monitoring for coordination.

We will first discuss differences between the optimal sampling theory and the collaborative coordination environment, and then discuss the implication of these factors on a proposed sampling model adapted to this environment.

A. Certainty Does Not Decay Upon Sampling

A fundamental difference between the optimal sampling paradigm and the current paradigm is that traditional monitoring paradigms are concerned primarily with monitoring and adjusting the current status of the system, or retrospective determination of trends in the trajectory of the system status. In the current schedule-monitoring paradigm, information is sampled primarily to gain insight prospectively into the future state of the system to anticipate future events. The operating schedule is initially established, but the components of the system (personnel, equipment, resources, patient) are continually monitored to determine whether the proposed schedule can be followed, or needs adjustment. Uncertainty about a given data point (e.g., surgical cases) does not necessarily increase over time; it often decreases or remains constant. For example, the status of a given surgeon scheduled for surgery is either known or unknown. If the status is unknown, the uncertainty can only decrease. If the status is ascertained as "available for surgery," then the uncertainty level is reduced, but still inherent in the sense that future events are never certain. Significantly, this uncertainty does not intrinsically increase over time, unless other system or schedule changes propagate new uncertainty through the system. Similarly, the determination that a particular piece of equipment is available for surgery does not become degraded over time in the same sense that the validity of an altimeter reading in an airplane cockpit decays as after the reading is taken. In contrast to the continual sampling of continuously changing visual displays, information sampling for scheduling is a process in which the initial information sampling results in an incomplete, imperfect representation of the situation. These inaccuracies can pertain to the type of procedure, the time required for the procedure, the type of equipment needed for the procedure, or even whether or not the procedure will be performed. Information that is missing can include patient positioning needs, patient status, room status, staffing levels, and staff status. Thus, in classical sampling, the uncertainty about the system status starts near zero, and degrades until the information is resampled, while in the current schedule-monitoring paradigm, uncertainty starts at a higher level and is reduced somewhat with each sampling, until the onset of a scheduled event.

B. Threshold for Monitoring is Dynamic

The inaccuracies and uncertainties cited above are tolerated because of the dynamic nature of the coordination process. Attempts to resolve all uncertainties too early would likely result in wasted coordination efforts, as plans may be changed by nearly any of the actors (nurses, anesthesiologists, surgeons, patients), or by forces beyond individual control, such as the addition of an emergency surgery to the schedule, or the cancellation of a planned case.

However, as the appointed time for a given procedure approaches, the tolerance for ambiguity decreases. There are deadlines for determining information with certainty, and the cost of a missed deadline influences efforts to sample information. As the threshold of tolerance approaches, the coordinator (CN) expends efforts to resolve the ambiguity. Expressed in the simplest terms, the tolerance threshold for uncertainty in the status of the schedule decreases as time passes, and approaches zero as a deadline (e.g., the case's start time) approaches.

For example, for any given case, the exact patient status is verified (disambiguated) roughly one hour prior to surgery. Before that time, general information regarding patient status is known, but specifics may be limited. Approximately an hour prior to the procedure, the CN was consistently observed calling the floor nurse or talking face-to-face with the surgeon or anesthesiologist to resolve any remaining ambiguity before final preparation for the case begins.

According to the optimal sampling theory, the threshold for sampling was generally considered constant (see [10] for exceptions), and the sampled information decayed over time. In the current model, the information does not decay—it remains relatively constant, but the threshold does not remain constant; it decreases as time passes. However, in both cases, when the level of uncertainty exceeds the threshold for uncertainty, sampling is initiated.

C. Information Sources and Their Characteristics: Reliability and Access Effort

The paradigm used in many of the previous examinations of optimal sampling theory is the scanning of visual displays. The

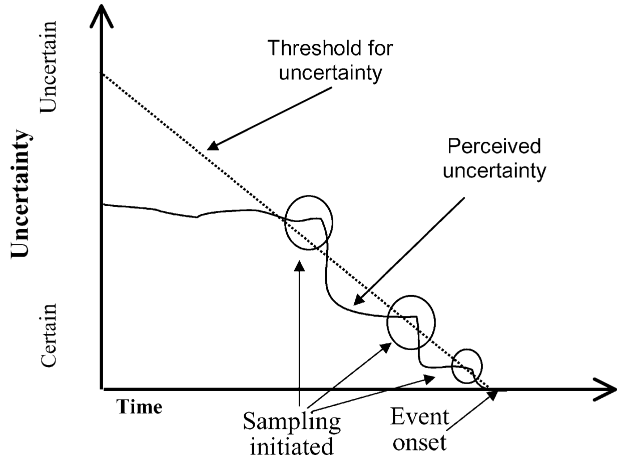

Fig. 1. Simplified model of information seeking distributed over time. Sampling is initiated when the threshold for uncertainty is crossed. Sampling does not eliminate all uncertainty, and the threshold approaches zero at the onset of an event (e.g., case start).

appeal of this paradigm is its relative simplicity of factors. However, in monitoring complex environments for the maintenance of an OR schedule, the information sources are rarely visual displays. Rather, the information sources are sampled through the three classes of information previously noted: information technology, such as pagers, phone calls, documents and information systems, direct observation of events within the OR suite, and personal interactions and social networks.

Unlike visual displays, which generally have relatively constant accuracy and information-access cost, each of these sources of information has its own profile of reliability and information-access cost, which can also change over time. Consequently, the threshold for sampling each of these sources of information is also dynamic and independent of the thresholds of the other sources of information. For example, information systems are often more accurate and reliable than social networking when planning further into the future, and are easy to use for such functions. In contrast, for gathering information about events in the immediate future, information systems are often inaccurate, as they do not contain the most up-to-date, informal knowledge possessed by the distributed, collaborative social network. Understanding the characteristics of the various sources of information—as well as the dynamics of the underlying parameters that the information sources represent—helps the CN decide which sources to use at any given stage of the scheduling process.

D. Sampling Model

Based on the characteristics enumerated above, it is possible to create a simplified model of information sampling as it occurs in the OR scheduling task (Fig. 1). In this model, the uncertainty remains relatively constant (i.e., information validity does not significantly decay), and is reduced when information sampling is initiated. However, uncertainty is not necessarily reduced to zero after sampling. The reduction in uncertainty depends on the source of information used to sample the system status. In the context of the model, sampling efforts are increased as the perceived uncertainty approaches or exceeds the threshold for uncertainty. As a critical event or deadline (e.g., case start) approaches, the threshold for ambiguity approaches zero.

The figure presents a simplified model. A more sophisticated model could include the fact that thresholds for uncertainty are not necessarily linear, and that there are different thresholds for information from different sources.

However, despite the simplified nature of the model, it provides utility. The choice to sample a given information source is related to the effort required and the perceived accuracy or reliability of the information. When provided with multiple possible sources of information, the CN will not necessarily chose the source with the highest accuracy. Our observations suggest that the CN will chose the one that provides **sufficient** level of detail for the given state of the system with the **minimum** level of effort. As the effort required to sample a particular source of information increases, the threshold for sampling that information source increases; as reliability increases, the threshold decreases.

Unlike in process control, nuclear power, and aviation domains, it is difficult to determine what an ideal sampling strategy would be in the OR environment. The OR environment contains a much greater level of inherent uncertainty than the traditionally studied domains of optimal sampling theory. Thus, it may be difficult to fully apply the same type of formal optimal-sampling models. Despite difficulty, the results of the current study do still suggest support for the basic tenets of the model. Based on interviews and observations, the CNs seemed to be aware of a number of factors when choosing to sample information. They were acutely aware of the limitations in the reliability of information from the different sources of information. They were also conscious of the amount of effort needed to obtain information from given sources, and wished to minimize wasted efforts in information seeking.

In considering the CN schedule-monitoring strategy proposed above, it should be emphasized that coordinating was observed to be a collaborative, team process spread out among different actors. Reliance on informal social networking to resolve ambiguous or inaccurate data was a cornerstone of the information-sampling strategy. Furthermore, even though the system status at any given time contained a large degree of intractable ambiguity and uncertainty, the coordinating CN did not attempt to resolve all ambiguity immediately. Different information sources were tapped in succession to gradually resolve ambiguity as needed. In this sense, the planning itself was distributed over time.

VI. Conclusion

The question of how people sample information has been investigated extensively in aviation and process control, often in experimental settings, and rarely in the context of team collaboration. The goal of much of this research was to determine how a system could be monitored most effectively with a minimum effort. The framework of classical sampling theory provided an underpinning for expansion of these models into the field of scheduling and planning through teamwork and team processes. The general concepts used in optimal sampling theories in other domains proved applicable to the current domain, with some adaptation. Thresholds for uncertainty, information access cost functions, and the general queuing concept all contributed to the currently proposed model of information sampling in distributed-planning settings. Observations and interviews carried out in the field allowed us to understand the complexity of the setting, and expand our understanding of these concepts. In the inherently uncertain planning environment for medical surgery, we observed that the ambiguity of plans and resources is iteratively reduced through collaborative actions distributed over time and over team members. We observed the way in which the tolerance threshold for uncertainty was adapted over the trajectory of each surgical case.

The model we presented introduced an initial assertion regarding coordination behavior in this setting. The model should not be applied to determine the optimal sampling rate, as in other domains, but rather to demonstrate the principles that shape the behavior of the CN. Our analysis focused on the specific activities of the coordinator (CN) at a level of analysis of activities within one day. Expanding the model to a larger or smaller time scale could yield alternative models with different sets of factors influencing information sampling, thresholds for uncertainty, and information sources.

The conclusions of this field study have implications for the design of technical systems to support this type of large-scale collaborative system. Significantly, a major issue encountered is that not all requisite knowledge is captured by formal systems or processes. Typically, the design of information technology is the focus of efforts to support medical tasks through formalized knowledge. These systems often are based on an assumption that knowledge is contained in the technology, is accurate, and is complete when a plan is formed. Our field observations suggest otherwise. We found that information is often incomplete, ambiguous, or inaccurate. Much of the effort exerted for coordination is directed toward disambiguation of information, and increasing the certainty of a status assessment. Furthermore, the accuracy of an information source is not necessarily the factor that determines whether it will be used. The utility of information is also strongly influenced by the information access cost, and by the relationship between the accuracy and the current threshold for ambiguity. When examining different potential sources of information, the source used will be determined by the tradeoff of effort and accuracy, with the particular tradeoff function being determined by the threshold for ambiguity at the given point in time.

The information landscape observed was complex because the characteristics of information sources used to disambiguate the status of a system were not constant. The characteristics (e.g., reliability, accuracy, effort needed to acquire) differ between sources, and the characteristics of a single information source can differ dramatically over time, and depending on the state of the system.

Therefore, the design of support systems should consider strategies to support or facilitate aspects of the three classes of information sources discussed (information systems, direct observation, and social networking). A focus on formalizing all data or on relying exclusively on existing formalized data would most likely be counterproductive. Rather, if implementing a technology-based solution for a domain such as the one observed, it is important to provide support for opportunistic sharing of informal data. One strategy suggested by the current research is to focus on reducing the information-access costs for the user from all three classes of information sources. This may include providing tools that disambiguate the system status with minimal effort. For example, direct observation was often the most accurate but required greatest efforts. Technologies that extend the operator's ability to observe system status directly may prove to be a productive direction.

While the proposed model provides a promising initial step in quantifying the interactions of information sources, time, and thresholds for ambiguity, this model should be validated with further study, and expanded to formalize the dynamics of collaborative coordination. The type of field-based methodology employed in this study can be applied in a wide variety of domains, and is sometimes the only method to uncover the subtle factors that influence human performance in complex systems.

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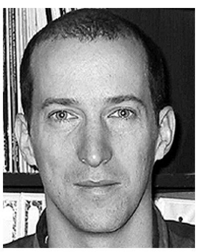

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