Decisions about critical events in device-related scenarios as a function of expertise

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Abstract

This paper presents the perspectives of personnel involved in decision-making about devices in critical care. We use the concept of “sharp and blunt ends” of practice to describe the performance of health care professionals. The “sharp end” is physically and temporally close to the system; the “blunt end” is removed from the system in time and space and yet affects the system through indirect influence on the sharp end. In this study, the sharp end is represented by the clinicians (nurses and doctors) and the blunt end by the administrators and biomedical engineers. These subjects represent the professionals involved in the decision-making process for purchasing biomedical equipment for the hospital. They were asked to “think aloud” while evaluating three error scenarios based on real events. The responses were recorded and transcribed for analysis. The results show differences in interpretation of critical events as a function of professional expertise. The clinicians (sharp-end practitioners) focused on clinical and human aspect of errors while the biomedical engineers focused on device-related errors. The administrators focused on documentation and training. These different interpretations mean that the problems are represented differently by these groups of subjects, and these representations result in variable decisions about devices. These results are discussed within a systems approach framework to help us assess the completeness of the problem representations of the subjects, their awareness of critical events, and how these events would collectively contribute to the occurrence of error.

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1. Introduction

Since the invention of the stethoscope by Rene Laennec in 1816 and the electrocardiogram by Einthoven in 1903, the use of technology in health care has grown by leaps and bounds. However, with the rising costs of health care and the magnitude of device-related medical errors, it is becoming increasingly important to identify guidelines for the purchase of biomedical equipment. There is increased interest in the application of theories and methods from cognitive science in the analysis and modeling of complex human activities [1]. It is only inevitable, therefore, that cognitive science makes its journey should appear in the complex, dynamic world of critical care decision making. The successful application of cognitive science principles to medical decision making, medical education, and medical expertise has spurred its progress, helped by the growing awareness that both theoretical and methodological approaches from cognitive science can contribute to the management of medical errors [1,2]. Medical errors have received recent...
attention from academic, healthcare, and governmental institutions following the medical error report from the Institute of Medicine, which named it as the eighth leading cause of death in the US [3]. There are various types of medical errors, including human errors, device-related errors, and errors that can be attributed to the social dynamics of interactions between people and technology in a distributed cognitive system [4].

The distinction between each type is often blurred, as errors are often multidimensional, with factors related to each of the different types of error contributing to its occurrence [5]. Early research into medical device-related errors showed that the errors in the use of equipment were more frequent and had more severe consequences than device malfunctions [6–8]. This in turn paved the way for research into human factors engineering [9–11]. Such research further suggested that even though hospital professionals often allocated blame to the user, the system and the device design are often the most important contributing factors. It also found that blaming the user is not an effective approach and that appropriate user-centered design of medical devices is a more effective approach and that appropriate user-centered design of medical devices is a more effective approach and that appropriate user-centered design of medical devices is a more effective approach [9–11]. Such research also suggests that health care professionals’ views of error vary based on their training and role in the organization, but this has never been directly studied, leading to this research on the attitudes of healthcare personnel to error [13].Because the way device-use errors are addressed and reduced in the real world often depends on what the decision makers view as the cause of the error, this paper ventures to look at how a professional’s expertise and position in a health care organization affects his or her view of medical errors.

2. Background and theoretical perspective

The paper is based on the premise that decisions made by various personnel involved in the design, development, and ultimately the purchase and use of biomedical devices in any institution influences the outcome and quality of health care provided. Understanding the process by which these personnel make decisions provides a formal way of creating a monitoring system for safety. Reason describes fallible decisions made by designers and high-level managerial decision makers as a basic posit of the framework that he discusses as a general view of accident causation in complex systems [5]:

“This is not a question of allocating blame, but simply a recognition of the fact that even in the best run organizations a significant number of influential decisions will subsequently prove to be mistaken. This is a fact of life. Fallible decisions are an inevitable part of the design and management process. The question is not so much how to prevent them from occurring, as how to ensure that their adverse consequences are speedily detected and recovered”.

Some social psychologists describe the fundamental attribution error as the tendency to blame bad outcomes on players’ personal inadequacy rather than attributing them to situational factors beyond their control [5,14]. Reason also uses the terms fundamental surprise and situational surprise, first introduced by Lanir [15]. Fundamental surprise is the profound discrepancy between one’s perception of the world and the reality, while situational surprise is a localized event that requires the solution of specific problems. Lanir compares the difference between the two terms to that between “surprise” and “astonishment,” illustrating it with an anecdote about the lexicographer Noah Webster. One day, Webster came home to find his wife in the arms of the butler. “You surprised me,” says his wife—to which Webster replies, “And you have astonished me.” While Webster experienced a fundamental surprise, his wife only experienced a situational surprise. The natural human tendency is to consider fundamental errors as situational ones and respond accordingly—this is called the fundamental surprise error. The recognition of such errors illustrates the importance of seeing the “big picture” during the analysis of errors and to look beyond the mere allocation of blame. An oft-ignored part of error analysis is the recognition of the “world,” i.e., the context in which the error occurs.

In this paper, we look at how different personnel perceive factors that contribute to errors that are farther away from the error in space and time than the operator end of the system.

When ascribing blame in an incident to “human error,” the implicated individual is at the sharp end of the system [5,16]. In medicine, such individuals could be the clinicians or technicians who are physically or temporally close to the patient. Government regulators, hospital administrators, nursing managers, and insurance companies are at the system’s blunt end, having an effect on safety by placing constraints on the practitioners at the sharp end. According to Reason, it is necessary to study the resources and constraints acting on the blunt end to effectively examine how these would eventually affect those who work at the sharp end [5].

Reason also distinguishes between two types of errors: active errors (whose effects are felt immediately) and latent errors (whose outcomes remain hidden or dormant within the system) [5]. The active errors are generally associated with the sharp end and the latent errors are generally associated with the blunt end. In the purchase of biomedical equipment, for instance, the purchasers, administrators, and the biomedical engineers (the blunt end) act on the suggestions of physicians and the nurses (the sharp end). Keselman et al. [17] de-
scribed a study they performed in a large hospital regarding the decision-making process for infusion pump selection. They found that even though they were able to identify the different professionals and groups involved in decision making, the flow of information among them was restricted [17]. They also identified the importance of collaborative communication technology that might be used to ease this process [17].

The concept of distributed cognition is used in this study to understand medical error in the context of critical care. This concept not only deals with the study of internal and external representations, but also deals with the distribution and propagation of knowledge between individuals and artifacts, as well as the transformations sustained by structures when used by individuals and artifacts. This new approach allows the study of cognitive phenomenon that are not observable at the individual level, such as cooperative work and socially distributed tasks such as those involved in health care, the nature of which is generally fluid and dynamic [1]. An important part of the “world” is the interaction between individuals. In health care, cognition is distributed across different groups and it is generally assumed that health care teams function in a collaborative manner in order to deliver health care efficiently and effectively [18,19]. This type of collaboration requires interaction, which has led to an increased focus on communication and teamwork. The composition of the team may represent different groups with their own agendas. For example, in an emergency room we may have a medical team, a surgical team, medical nurses, and trauma nurses working with the same patient at the same time. The inherent benefits and problems of such a situation are the same as with any example of divided labor—the most important benefit being an increased efficacy in terms of time and quality, and the most important problem being summarized by the expression—“the right hand is unaware of what the left does.”

The composition of the team itself is dynamic, depending upon various factors like the time of the day and the nature of the task involved. Information and cognition flows across these individuals, groups, devices, and the external world [18–20].

Ever since the Stone Age when people lived in caves and hunted together in bands, humanity has understood the importance of collaboration. Probably the most elegant examples of intellectual collaboration can be found in health care: the organization of health care providers into groups of physicians, nurses, and other personnel and the specialization within these groups. The intelligence required to solve a particular problem is often distributed across multiple individuals. When the cognitive load behind a task that requires collaboration for its execution is relatively low, and the decision to be made is easy, all members of the team have more or less equal standing. However when the cognitive load is high, the cognition involved is usually distributed in a hierarchical manner. Where such a hierarchy is ill-defined, and multiple factors have to be considered, no single individual or group can assume the mantle of leadership; various groups with various levels of expertise that may or may not overlap must confer before reaching a common solution [19].

Zhang et al. [4] describe a taxonomy of medical errors that is intended to classify different medical errors cognitively; associate these errors to the underlying cognitive mechanisms that play a causative role in error production; indicate and describe where, when, and why these errors can or will occur; and generate strategies for intervention. However, their work approaches medical error from the perspective of human errors. It is based on the premise that any recognized error can be traced to the actions of an individual or groups of individuals under specific situations. Malhotra et al. [21], on the other hand, explore the contribution of medical device design to errors and how current safety principles can be improved through better engineering. They discuss the use of cognitive techniques to study error scenarios in the critical care setting and builds relationships between the device and various medical error causing entities. The errors and their relationships were then qualified on the basis of their modifiability. The possibility of including safety features to counter these modifiable errors by engineering them into the device domain itself was explored and consequently these authors recommended modifications to the device design cycle. However, even if an intelligent medical error reporting system with the capacity to predict error was created on the basis of factors related to individual cognition, or even if a “perfect” medical device could create, medical errors would still occur. Therefore interventions based on these premises, as commendable and necessary as they are, would not be complete without adequate attention to the nature of the system in which these errors could occur. Our current paper not only aims to compare the perception of key players in the decision-making process in the selection of biomedical devices, but also provides possible interpretations about how people with different backgrounds and expertise process information differently to make decisions.

3. Methodology

3.1. Subjects

An earlier study revealed that the groups involved in decision making about device purchase were primarily composed of the following hospital workers: administrators, biomedical engineers, nurses, and physicians [17]. Based on this data, we selected nine subjects as a repre-
sensible sample of the group responsible for clinical and administrative decisions about the purchasing of medical devices for the hospital. These were two physicians (an anesthesiologist/critical care specialist and anesthesiology resident), a physician’s assistant, two critical care nurses, two biomedical engineers, and two administrators.

3.2. Scenarios

A sample of scenarios was chosen based on examples adapted from the Food and Drug Administration’s (FDA’s) medical device report files and based on the FDA’s “Do It By Design-An Introduction To Human Factors In Medical Devices” [12]. The major protagonist in each of three selected scenarios was a different type of professional representing a possible problem with a medical device interaction. A clinical consultant assisted our team in choosing the scenarios by evaluating their adequacy and appropriateness for meeting our study’s goals.

A brief summary of each scenario is outlined below. The full scenarios, as presented to the subjects, are in the Appendix.

(1) Scenario One (heparin-infusion pump-physician scenario). A patient receives intravenous heparin via an infusion pump. He is to receive a bolus for an hour, at the end of which he is to be placed back on the maintenance dose. A physician changes the dose at the end of the hour. But he overlooks pushing the “confirm” button for the dose change, and the patient continues to receive the high bolus dose. The pump keeps beeping as an indicator something is wrong, but no one notices or pays attention to it, including a member of the patient’s family who was in the room overnight. A nurse discovers the error the next morning.

(2) Scenario Two (oxygen-ventilator-ICU team scenario). In a pediatric ICU setting, an infant receives oxygen through a ventilator. A physician orders a change in the flowrate from one to one point five. Neither he nor the rest of the critical care team are aware of the fact that the device can only be put on discrete settings of one, two, three, etc. and does not operate when the dial is between these numbers. Consequently the child receives no oxygen at all. On discovering the error the child is given higher flow rates and rescued.

(3) Scenario Three (nitroglycerine-infusion pump-nurse scenario). The condition of a patient in the ICU is deteriorating, and multiple interventions are being performed at the same time. The nurse receives four drug orders in one measuring unit, and a fifth order for nitroglycerine infusion in another unit of dosage. She ends up programming the nitroglycerine infusion pump with a dosage in units similar to the other four orders. The patient gets overdosed and experiences a dangerous fall in blood pressure.

3.3. Procedure

All nine subjects were asked to read Scenario One and then to answer a set of semi-structured questions designed to elicit a think-aloud protocol. Our aim was to obtain their assessment of the causes and severity of the error in the scenario. The same procedure was repeated for Scenarios Two and Three. The rationale for the questions and probes are discussed below. All subjects were interviewed face-to-face, except for the two administrators, who were interviewed over the phone. All interviews were audiotaped and then transcribed for analysis.

Questions and rationale:

(1) Please provide a summary of the scenario. This question was asked to assess the accuracy of the participants’ representation of the problem. This question also provided the link between the internal representation of the problem and the decision-making process that would be evoked by the following questions [22–24].

(2) What are the causes of the error in the scenario? This was asked to assess the participant’s perception of the source of the error, without prompting them to identify a human component.

(3) Please rank the causes given in (2) above on a scale of one to five, five being the most serious and one being the least serious. This question was asked to assess the participant’s perception of the relative seriousness of various causes.

(4) Who (or what) do you think was responsible for these errors? This question was asked to assess the participant’s perception of the human component (and attribution) of the error.

(5) What steps could be taken to prevent these errors? This was asked to assess the subject’s perception of potential safeguards.

The transcribed responses were analyzed using thematic coding [25]. Thematic coding gives rise to categories that are not predefined, but emerge in the course of data analysis and are thus data-driven. This is similar to the grounded theory approach to data analysis [26]. In such a framework, the researcher approaches data without a precisely stated hypothesis, allowing a theory to emerge from the data itself, under the assumption that the theory is grounded in the data (thus the term grounded theory). This research approach is appropriate for the investigation of complex topics in their naturalistic contexts and is concerned with “understanding behavior from the subject’s own frame of reference.”
In the thematic coding scheme, the transcribed protocols were parsed into meaningful segments, where they represented one causal or explanatory statement that consisted of a sentence clause, a sentence, or, in some cases, the grouping of a main sentence and one or two follow-up sentences. The iterative coding process was a combination of inductive/"bottom-up" and deductive/"top-down" coding. Some preliminary coding categories (typically, top-level) were based on the interview questions and study objectives. Other, lower-level categories emerged in the process of three rounds of careful data review by three investigators, with the first two rounds being performed individually and the last round being performed by all three of the investigators to reduce variability. Once final coding categories were developed, they were grouped and organized by the same investigators. The thematic categories identified in the three scenarios are shown below. Each of these categories represents an event, a series of events, possible interventions, or discrete factors that contributed to the error. For example, the environment category is an important factor identified by the subjects as contributing to error and shall be discussed in detail later. We considered the working definition of a health care event to be a planned action or a group of related planned actions in health care. Thus an error could also be similarly and broadly defined as an event or a series of events whose end outcomes are unacceptable and unintended. This is similar to Reason's working definition of error [13]:

"Error will be taken as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency".

### Table 1

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>User error</td>
<td>Included the recognition of an inappropriate user, lack of knowledge regarding the device involved, cognitive errors like lapses in memory, misinterpretation of the order, etc.</td>
</tr>
<tr>
<td>Order format and interpretation</td>
<td>Some of the subjects identified that the way the order is presented in terms of dosage could make a difference on how the order is understood</td>
</tr>
<tr>
<td>Device design flaw</td>
<td>The presence of devices whose features were unsatisfactory, was traced to one of these three processes</td>
</tr>
<tr>
<td>Device acquisition</td>
<td></td>
</tr>
<tr>
<td>Device evaluation</td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>The nature of the environment that leads to multi tasking on part of the health professionals, the way devices are arranged and setup was also identified</td>
</tr>
<tr>
<td>Device setup</td>
<td></td>
</tr>
<tr>
<td>Labeling of devices</td>
<td></td>
</tr>
<tr>
<td>Training</td>
<td>The subjects commented upon the presence or absence of training required to use the devices</td>
</tr>
<tr>
<td>Absence of double-checking</td>
<td>The subjects identified this category across the three scenarios; referring to the process by which the concerned professional would check to see if the patient was doing well, the devices involved were working fine and the orders were carried out correctly</td>
</tr>
<tr>
<td>Communication</td>
<td>The subjects identified the gaps in communication between the health care team and/or the purchasers or evaluators of the concerned device</td>
</tr>
<tr>
<td>Family</td>
<td>This category was specific to Scenario One, where the family is explicitly mentioned</td>
</tr>
</tbody>
</table>

Each category refers to an event, possible intervention or any contributing factor to the error that occurred in each scenario.

### 4. Results

The final categories and a brief explanation of their context as identified through our coding scheme for all the three scenarios are shown in Table 1.

Table 2 presents the frequency of categories identified by each subject for each scenario expressed as a percentage of the total number of categories of events identified by all the subjects per scenario. The table shows that in two out of the three scenarios the expert physician identified most categories of events (in Scenario One 88.9%, in Scenario Two 54.6%). A nurse identified most categories in the third scenario (66.7%). However across all scenarios, nurses show the highest mean performance in identifying the different categories (Mean = 60.3%).

Table 2 also presents the mean percent of categories identified by the subjects represented as a function of the sharp and blunt ends of health care. Amongst the nine subjects interviewed, the physician, the resident, the physicians' assistant, and the two nurses could be said to represent the sharp end, while the two biomedical engineers and the two administrators could be said to represent the blunt end of health care. As shown in the figure, the subjects at the sharp end of practice identified 62.2% of event categories in Scenario One, 38.1% in Scenario Two, and 43.3% in Scenario Three. The subjects at the blunt end of the practice identified 38.9% of event categories in Scenario One, 29.6% in Scenario Two, and 35.4% in Scenario Three. The personnel at the sharp end of the healthcare practice were able to identify significantly higher number of errors than the people at the blunt end of the practice, across all three different scenarios.

We analyzed each scenario and identified a series of issues to be considered in error evaluation. We now discuss the perception of the subjects relative to these issues.
4.1. Scenario One: heparin-infusion pump-physician scenario

**The task involved:** Changing the dose of a drug.

**Device involved:** Infusion pump.

**Drug:** Heparin, an anti-coagulant.

**Subgoals and their failures:**

1. Ordering the change.
2. Communicating the order.
3. Documenting the order.
4. Performing the change ordered.
5. Verifying “right drug, right dose, right order, and right patient.”
6. Programming the pump.
7. Pressing confirm (not done).
8. Documenting the performance.

**The setting:**

1. A physician operated the pump.
2. Neither he nor the nurses noticed the error.
3. The pump alarm was on all night.
4. Even the family did not notice the error.

**The perceptions of the subjects:**

The obvious error—the failure of the physician to press the confirm button—was noticed by all of the subjects. The resident and one of the nurses mentioned that the physician was an inappropriate user. This observation probably reflects those user's experience or may even be an instance of hindsight bias, as it is not unknown for members of a health care team higher up in the hierarchical ladder, like a physician, to perform some of the duties of other staff, especially in emergency situations. The expert physician was the only person who identified that the erring physician failed to notice the need to press confirm button. While all of the subjects at the sharp end, except the physicians' assistant, noticed that there was no communication between the erring physician and the nurses, only one of the administrators at the blunt end noticed this. The expert physician and a nurse noticed that the way the order was formatted in terms of drug dosage could have obviated this in turn reflects the expert's superior clinical knowledge and its practical application. Both the clinicians (a physician, a resident, and a physician's assistant) and the biomedical engineer suggested that the pump in question itself might have been flawed since the alarm went unnoticed all night and it continued to provide the bolus dose even during the alarm. Only the biomedical engineer recognized that the alarm should have been evaluated more closely with respect to the alarm and the need to press the confirm button. These results were surprising since we expected that the administrators and the biomedical engineers would notice this. These professionals represent the major decision makers in the purchase of biomedical equipment. The nurses, who traditionally have the most interaction with family members, held that the role of the family was not significant in this case. This probably reflects their experience with family members who would not recognize the significance of the alarm. The expert physician did not consider training to be a significant factor in this case and would expect errors to occur in these circumstances, while other subjects believed that training would have helped to prevent them.

4.2. Scenario Two: oxygen-ventilator-ICU team scenario

**The task involved:** Providing an infant with oxygen.

**Device involved:** Ventilator.

**Drug:** Oxygen inhalation.

**Subgoals and their failures:**

1. Ordering the oxygen.
2. Communicating the order.
3. Documenting the order.

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**Table 2**

The frequency of categories identified by each subject for each scenario expressed as a percentage of the total number of categories identified by all the subjects.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Scenario 1% (Total categories identified = 9)</th>
<th>Scenario 2% (Total categories identified = 11)</th>
<th>Scenario 3% (Total categories identified = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurse 1</td>
<td>77.8</td>
<td>36.4</td>
<td>66.7</td>
</tr>
<tr>
<td>Physician</td>
<td>88.9</td>
<td>54.6</td>
<td>25</td>
</tr>
<tr>
<td>Resident</td>
<td>55.6</td>
<td>36.4</td>
<td>50</td>
</tr>
<tr>
<td>Nurse 2</td>
<td>55.6</td>
<td>36.4</td>
<td>41.7</td>
</tr>
<tr>
<td>Physicians assistant</td>
<td>33.3</td>
<td>Sharp end mean = 62.2</td>
<td>27.3</td>
</tr>
<tr>
<td>Administrator 2</td>
<td>44.4</td>
<td>45.5</td>
<td>41.7</td>
</tr>
<tr>
<td>Biomedical engineer 2</td>
<td>44.4</td>
<td>36.4</td>
<td>25</td>
</tr>
<tr>
<td>Administrator 1</td>
<td>33.3</td>
<td>18.2</td>
<td>33.3</td>
</tr>
<tr>
<td>Biomedical engineer 1</td>
<td>33.3</td>
<td>Blunt end mean = 38.9</td>
<td>18.2</td>
</tr>
<tr>
<td>Administrator 1</td>
<td>33.3</td>
<td>18.2</td>
<td>33.3</td>
</tr>
</tbody>
</table>

Each category refers to an event, possible intervention or any contributing factor to the error that occurred in the scenario. The mean percentage of categories identified by the subjects, represented as a function of the sharp and blunt ends of the task is also included in the table.
4. Performing the change ordered.
5. Verifying “right drug, right dose, right order, and right patient.”
6. Operating the ventilator knob (error in using continuous values instead of discrete ones).
7. Documenting the performance.

The setting:
1. Critically ill infant that rapidly became hypoxic when the knob was set at 1.5.
2. The knob moved smoothly.
3. No one on the team knew or communicated the fact that a continuous setting was not possible with that particular pump.
4. The feasibility of such a ventilator in a pediatric setting was questionable.

The perceptions of the subjects:
Every subject felt that the error in this scenario was due to the lack of training or in-servicing the equipment, since no one on the critical care team seemed to know specifics about the device control. The obvious device design flaw was noticed by most of the clinicians (4 out of 5, or 80%) but neither administrator. In addition, four of the six clinicians stated that the device should have been removed. Two administrators and a resident felt that lack of communication between the biomedical engineering team and the clinical team was responsible for the error. The physician traced the errors to the lack of knowledge about the device that led to a poorly formatted order, saying that if the order had been given in a different dose at different intervals, it would have had the same therapeutic effect without providing an opportunity for error. The two biomedical engineers acknowledged the lack of an appropriate evaluation before the device was introduced into the clinical setting, a response consistent to their area of expertise. The nurse, given her task of working with the pump daily in practice, suggested placing a warning label on the pump that would alert users to likely errors in operation.

4.3. Scenario Three: nitroglycerine-infusion pump-nurse scenario

The task involved: Changing the dose of a drug.
Device involved: Infusion pump.
Drug: Nitroglycerine, an antihypertensive.

Subgoals and their failures:
1. Ordering the change.
2. Communicating the order.
3. Documenting the order.
4. Performing the change ordered.
5. Verifying “right drug, right dose, right order, and right patient” (the error was giving the wrong dose of the drug).
6. Programming the pump—(the error could have occurred while the pump was being programmed).
7. Documenting the performance.

The setting:
1. Critically ill patient, multiple interventions being performed.
2. Nurse receives voice orders and is to perform five medication changes, of which four drugs are in a different unit than the nitroglycerine.
3. The device is not easily accessible.

The perceptions of the subjects:
Every subject with the exception of the administrator identified the user error in programming the wrong dose for the pump. Most of the subjects (8 out of 9) identified the role of the environment in the error. They believed that the dynamic environment, which required multitasking on the part of the nurse, contributed to her error. They also believed that the way in which the order was written and the variability with which the drugs were ordered could have played a part in the error. The administrators went on to say that the nurse did not check against these written orders. However, they failed to identify the fact that nitroglycerine given in as high a dose as described in the scenario would have caused a sharp fall of blood pressure in a manner of minutes, while interventions were still being performed on the patient. This reflects the administrators’ lack of clinical expertise in evaluating the scenario. The only other person who identified this category was a nurse who was referring to the absence of a more synchronous double-checking by the other members of the team.

5. Discussion

We interpreted the results within the theoretical framework of distributed cognition. Below we discuss the nature of expertise and of the task in relation to the domain in question.

5.1. The ‘‘Pipe and Filter’’ analogy

It is a common human tendency to look for a scapegoat, and often the personnel at the sharp end bear the brunt of the blame. Cook and Woods [16] identify four reasons why human operators are blamed for adverse outcomes. The first reason is the availability of human operators; they are visible and formally responsible with the safe functioning of the system under their charge. The second reason is the difficulty in retracing or
recreating the causal chain of events that led to the system failure. Eventually this chain will include a human whose actions will seem inappropriate in hindsight. In absence of adequate knowledge on how these human operators think, any analysis would fail to demonstrate the rationale and the perspective behind the seemingly causative human action. The third reason that Cook and Woods mention is that the judgment of human error is made in situations where humans usually show an exemplary performance. Failure of such systems is rare, even in the presence of ample opportunity for error, because expert human performance is able to avert such errors. As the performance of the human operators improves after the inception of the system, there arises the possibility to attribute the resultant improved system performance to the system itself rather than to the human operators. The fourth reason for identifying human error as a verdict, according to Cook and Woods, is the phenomenon of hindsight bias, which is the tendency of people to “consistently exaggerate what could have been anticipated in foresight” [28]. Accordingly critics will not be able to make unbiased judgments because of their prior knowledge of the outcome. Cook and Woods [16] go on to mention “hindsight bias is the greatest obstacle to evaluating the performance of humans in complex systems after bad outcomes.”

This paper takes the above arguments into consideration and looks beyond the allocation of blame. Cole and Engstrom [29] suggest that the natural unit of analysis for the study of human behavior is an activity system, comprising relations among individuals and their proximal, “culturally organized environments.” A system that consists of individuals, groups of individuals, and technologies can be construed as a single indivisible unit of analysis. A system is thus an intangible abstract entity, yet it is very real and often needs to be addressed as such. For the purpose of looking beyond human and device factors, we required a framework to understand the system in consideration. For this purpose, we constructed an analogy to help us interpret our results.

Consider the sequence of events that happen to a patient after the person seeks health care [30,31]. These events form the flow of health care, which can be assumed to be smooth under normal conditions. This flow has a direction, ideally towards the goal of health, and is contained in a pipe that represents the health care system. If the conditions are emergent, then the flow itself is turbulent and this turbulence depends on a constant that represents many factors like the capacity of the pipe (the health care system), the nature of the care required (for example, critical care), and environmental constraints (like a limited number of trained personnel or limited technology). This is illustrated in Fig. 1. At any point in time, a cross-section of the pipe represents an event of health care in progress. An examination of the cross section will reveal the event and the distributed cognitive effort behind the event. The flow of health care also has a relation to the flow of information. Information flows across the healthcare system a long time, as well as across people and the artifacts included in any single event. This analogy can be extended further. The wall of the pipe that constitutes the system does not merely have a single layer. In fact it can be described as having a definite structure. The clinical team that

![Fig. 1. (A) The sieve analogy. Information flows across the health care system in two or more dimensions. This figure represents the health care system (the pipe); the block arrows represent the flow of health care, while the line across represents a single dimension of the flow of information, as well as time. (B) A representation of the cross section of the pipe, which shows a cognitive perspective of an event based upon Roth’s Cognitive Triad. However, this cross section may also be redrawn—a web instead of the triad can accommodate Berg’s socio-technical approach. A more complex, yet more theoretically adequate diagram can be used to represent distributed cognition across different agents, tools or artifacts.](image-url)
constitutes the sharp end lines the innermost layer as do the devices and other non-human agents, while other personnel like the managers, administrators, insurance companies, and biomedical engineers from the blunt end form the outer layers. Abstract constructs like health care policies, economic policies, laws, and regulations pervade the outer layers and modulate their activity, which further affects the activities at the inner layer. The activities of the inner layer are affected in turn by abstract concepts like medical ethics, clinical protocols, and guidelines.

Every cross-section of the pipe is like a snapshot in time and shows a health care event in progress. This model can accommodate Roth's cognitive triad, Berg's socio-technical approach, and Hutchins's concept of distributed cognition [32,33]. This is illustrated in Fig. 2. The concept applied depends on the context of the event being analyzed. For example, Roth's triad that focuses on the individual could adequately explain the actions of a physician entering orders using an order-entry system but would not be adequate to describe the interaction of a clinical team with a number of devices used on a patient simultaneously [34]. The latter situation could be explained within the broader concept of distributed and collaborative cognition.

A discernible difference in health care quality occurs after every event, which is represented by a cross section of the pipe. An error is at the simplest level just an event, a single cross section of the pipe. The difference between an error and an event is that the quality of care passing through the pipe is altered by the error. A filter (similar to a water filter) represents an event that corrects for the quality of the health care flowing through it, if a previous event has either not occurred or has occurred with an unacceptable result. Health care is riddled with such filters, often in sequence. For example, a physician calls back to check if the order was carried out, or a nurse checks against the written order after a shift change. It has been shown that even experts commit errors almost as frequently as novices, yet they correct themselves more frequently and accurately [35]. Therefore, it may not be far-fetched to say that even while an effort may be made to avoid an error, an equal effort could be made to catch the error.

By using this analogy of the pipe and the filters, an event that leads to an error can be identified by examining the quality of care before and after each event. The faulty filters (or screens) behind the event can be identified with respect to the frequency as well as temporality of their occurrences. An example of a filter is a nurse checking orders soon after she signs in for her shift. But if the event that leads to an error happens after she has checked her orders, the filter can be said to have let the error through (missed the error) and is thus faulty. These filters can be considered similar to a schema where prior conception is used to screen irrelevant information in problem-solving tasks [36]. These schemata develop as a function of expertise.

5.2. Application of the filter analogy to the perception of events and errors

Table 3 shows a sample of the data interpreted within the context of the filter analogy. The two columns at the extreme right represent the added inferences with respect to whether a filter was identified and the frequency with which a particular filter was identified. The events were analyzed by comparing the table with the original segmented transcript. We identified the filters using the following criteria.

![Fig. 2. A representation of the cross-section of the “pipe,” which shows a cognitive view of an “event” based on the theories of distributed cognition. The vertices represent important agents in the event, and as the number of these vertices increase the number of possible interactions between them also increase.](image-url)
A filter is any event that rectifies the quality of a health care event (e.g., a nurse checking on a patient, or a surgeon asking for an instrument count before he closes an incision).

A filter could follow the occurrence of an error, which could be an error of omission or an error of commission (e.g., a physician who forgets to perform part of a routine physical examination, realizes the fact when he reads his notes, and performs the necessary test).

A filter may precede the event if the filter itself constitutes an important event in quality control (e.g., a nurse checks to see that the medicine contained in the storage cabinet has reached its expiration date).

We identified four filters in Scenario One:

1. **Failure to recognize confirmation.** The physician recognized that the erring physician in the scenario not only failed to complete the required action (by failing to press the confirm button), but also failed to notice that confirmation was required. This was the unique filter that the other personnel missed.

2. **Device design flaw.** Three out of the nine subjects (the physician, a nurse, and the physician’s assistant) recognized the device flaw (an inadequate alarm). They also identified that the need for confirmation after performing an action was unclear.

3. **Absence of double-checking.** By far, this was the most common filter identified, by eight out of the nine subjects, where the nurse failed to check on the patient and the orders.

4. **Evaluation of the devices.** This filter, identified by one of the biomedical engineers, refers to the process of evaluation of a device before it is introduced to the clinical environment. This is considered a filter because as the process corrects for the inherent device errors that should have been caught by the biomedical engineers who conducted the evaluation. This is an instance of an expert recognizing a relevant error in his/her area of expertise.

We identified four filters in Scenario Two:

1. **Training.** Every subject identified this filter, with each mentioning that none of the players in the scenario knew about the peculiarity of the device in that it allowed only discrete volumes. They all attributed this to the lack of training.

2. **Order format.** The physician identified as a problem the decision to deliver that particular dosage in absence of knowledge of how the device worked, which was an error. The physician also noticed that, in this particular scenario, the error was recognized before an adverse event occurred (a near-miss).

3. **Device acquisition.** The physician and one of the biomedical engineers described this filter, which refers to the actual process of acquiring a device for future use by the hospital. The physician held that the presence of such a device in a pediatric ICU made no sense.

4. **Evaluation of the devices.** As in the scenario above, the same biomedical engineer identified that the inherent device errors should have been caught during the evaluation of the device. This engineer possibly identifies this filter more than once as it has direct relation to that individual’s current work, which involves direct contact with the users during evaluation and maintenance of equipment.

We identified three filters in Scenario Three:

### Table 3

<table>
<thead>
<tr>
<th>Error identified (broad category)</th>
<th>Error identified (specific category)</th>
<th>Frequency</th>
<th>Filter Failure</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Error</td>
<td>Failure to hit confirm</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Error</td>
<td>Failure to notice confirmation required</td>
<td>2</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>Order Format</td>
<td>Delivery</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>Communication with family</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Error</td>
<td>Inattention</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Order Format</td>
<td>Delivery</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device design flaw</td>
<td>Confirmation needs to be done (clearer)</td>
<td>1</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>Training</td>
<td>Recognizes error occurrence even with training</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device design flaw</td>
<td>Needs to be louder</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Error</td>
<td>Bad use</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device design flaw</td>
<td>Alarm</td>
<td>3</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Environment</td>
<td>Task overload/multitasking</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non specific</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family</td>
<td>Role is important</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Order Format</td>
<td>Delivery</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absence of double checking</td>
<td>Absence of double checking</td>
<td>1</td>
<td>Y</td>
<td>1</td>
</tr>
</tbody>
</table>

The last two columns represent the added inferences with respect to whether a filter was identified, and the frequency with which it was mentioned.
(1) **Order format.** This filter was identified by seven of the subjects. But there was wide variability in what they understood within this context. The personnel at the sharp end and one of the biomedical engineers held that the variability in ordering the drug dosage (in terms of the units of the drug) could allow for such an error to happen and that this could have been avoided by formatting the order in a more understandable form. The administrators, however, held that the order should have been in the written form, in contrast to the verbal form as stated in the scenario, to prevent the error.

(2) **Absence of double-checking.** Three subjects—a nurse and the two administrators—identified this filter. The two administrators held that the nurse did not double-check on her orders, which would have required the orders to be in writing. The nurse, however, referred to double-checking the actions of the erring nurse at the time that the error occurred, a more dynamic check that could have carried out by any other member of the health care team.

(3) **Device design.** A nurse and two biomedical engineers mentioned that the presence of inbuilt constraints or the necessity for standardized input could have prevented such an error by not allowing the erring nurse to input a wrong dose.

At this juncture, we should point out the different interpretation of Scenario Three by the administrators. In this scenario, the dose of nitroglycerine that was administered by the erring nurse was extremely high. Nitroglycerine, especially when given intravenously, is a fast-acting drug. Therefore the effects of the error would have been immediate, with no time available for the order to be written or checked against the order. The administrators however held that the error occurred because the order was not written down and the nurse did not check her actions against the written order. This reflects their poor understanding of the clinical circumstances of this scenario. The filters that the administrators identified, which were the double-checking on part of the nurse against the written orders of the physician, reflect the traditional expectations that administrators would have of the clinicians.

As mentioned earlier, the pipe and filter analogy is based on the cognitive concept that experts are able to correct themselves in time by being able to identify critical points or events that would lead to an error. This concept is considered valid given that the data show differences among the expert physician, resident, and physician's assistant respectively as a function of expertise development. Using this analogy concept as a qualitative tool, we can now say with more confidence that the clinical personnel at the sharp end had a better representation for making accurate decisions about critical events than the administrative or engineering personnel. The results emphasize the difference between two groups of health care professionals, those at the sharp end and those at the blunt end of health care practice. The apparent gap in clinical insight on the part of the blunt end might reflect the poor understanding of the blunt end personnel regarding the practical issues that are encountered in the clinical environment. The importance of this gap lies not only in evaluating error, but also in broader issues such as the purchasing of biomedical equipment, and the introduction of electronic tools and other applications that can result in a major change in workflow [17]. This gap in insight can be ascribed to a lack of situational awareness, which is the absence of awareness of things that are happening in a particular situation (such as clinical practice) and the reasons for their occurrence [5,37]. This lack of situational awareness is shown by the two administrators as discussed above.

The pipe analogy also suggests the importance of collaborative cognition in the health care environment [18–20]. The subjects in the study consistently identified events that require effective communication, teamwork, and a workload distribution. They also identified the importance of the role of the team players. For example, in one scenario, the subjects identified that it was inappropriate on the physician’s part to have handled the infusion pump, a task that is traditionally carried out by the nurses in most settings. In clinical settings it is not uncommon to see instances where the often-indistinct lines that define the roles of each team player blur. But most situations in which such transgressions occur and are acceptable are when a player at a higher level in the hierarchy performs a task usually intended to be carried out by a person lower down in the hierarchy, as in the scenario presented to the subjects. Thus, in the absence of the occurrence of the error, such an event would not have been identified as abnormal. It is only in retrospect and probably due to hindsight that this seemed important to them. We argue that even though such an observation can be attributed to hindsight bias, it does not diminish the importance of the observation. As mentioned earlier it may be possible that the physician did not have adequate training or exposure to such pumps. A possible acceptable alternative action that the physician could have adopted in the scenario was to effectively communicate the change in orders to the nursing staff, both verbally as well as in writing. To be effective, communication should also have an emotional component. A physician could expect a better response to his orders if he has a better rapport with his team. Similarly, we have to identify the importance of collaborative cognition amongst the purchasers, evaluators, and users of devices. Each of these groups consists of experts with differing areas of expertise, which may overlap. They all have different perspectives that depend on their cognitive backgrounds with respect to their
experiences, training, level of expertise, and traditional roles in society. It is therefore important for these groups to reach a consensus before an important institutional decision is made [17].

Critical care environments are complex and dynamic, requiring multitasking and decisions to be made at different points in time. The conditions that influence these decisions cannot always be predetermined as they evolve with time. The pipe and filter analogy could be applied to the analysis of errors or near misses to reconstruct the flow of events and to identify the predisposing factors.

6. Conclusion

The results show that the interpretations of the different individuals mirror their area of expertise. Because interpretation is closely related to representation, the representations of the problems are also different [1,36]. The clinicians identified critical clinical events, and the biomedical engineers identified critical events that pertained to devices. The administrators focused primarily on documentation and training. Because problem representation is in turn closely related to how people make decisions, our research raises the question as to whether such differences between the ends of health care may reflect on broader issues in institutional decision making, like the decisions regarding the interventions to reduce error, or the decisions regarding the purchasing as well as the employment of information technology and electronic tools.

Keeping with the current trends in the analysis of errors, we move away from the focus on the human aspect of error and its attendant allocation of blame to a single individual to a systems approach. Using the pipe and filter analogy as a theoretical framework, we reconstruct the system involved and recognize potential areas of intervention in the scenarios studied (filters and their failures). We used the analogy to help us assess the completeness of the problem representations of the subjects, their awareness of critical events, and how these events would collectively contribute to the occurrence of error. From this we conclude that no single individual has a comprehensive view of all the factors that contributed to error. Other potential uses of this concept would be to study the systems into which medical devices, information technology, or electronic tools are to be introduced to maximize their performance and utility and also to reduce the factors that contribute to mishaps. To take a page from the aerospace industry, using a systems approach to error could potentially convert a health care organization into a “high reliability organization”—a complex, dynamic organization that carries out its activities with a low incidence of mishaps and an almost complete absence of catastrophes [3,38,39].

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Appendix A. Scenario One: heparin-infusion pump-physician scenario

Around 8 pm, a patient was receiving a usual infusion of heparin per the heparin protocol, around 12 cm³/min (1200 U/h). Due to a change in circumstances, this patient was to receive a bolus dose of Heparin IV through the infusion pump. This bolus was ordered to change at the end of one hour back to the maintenance continuous dose. A physician at the end of the hour changed the drip rate but did not check the confirm button or notice the small confirm print warning on the panel of the pump. The next morning, a nurse entered the room upon hearing the pump alarm beeping. She noted an empty bag, and that the rate set on the pump was 200 cm³/min. The patient had received a bolus of approximately 18,000 units of heparin. When the nurse manager investigated the event, both nurses who were caring for this patient overnight denied changing the pump infusion at all. Of note, there was a patient’s family member in the room the entire night, though this person was never asked directly about what might have happened to the pump. Furthermore, the patient did not recall anyone changing the pump. Biomedical Engineering now has the case, and is investigating the pump. Preliminary report suggests that there was no problem with the pump but that it was mis-programmed.

Scenario Two: oxygen-ventilator-ICU team scenario

A pediatric ICU physician was treating a six-month-old patient with oxygen and ordered that the infant receive 1.5 L per minute. Within 3 min, the patient became hypoxic. At this point, the critical care team increased oxygen flow to 3 L/min for 10 min to compensate and was then ordered by the physician to be set to 2 L/min. Biomedical engineering told the critical care team that they set the flow control knob between 1 and 2 L/min not realizing that the scale numbers represented discrete settings (0 or 1 or 2 or 3, etc.) rather than continuous settings (1.1, 1.2, 1.3, 1.4, etc.). Hence, even though the knob rotated smoothly—suggesting that intermediate settings were possible—there was no oxygen flow between the settings.
Scenario Three: nitroglycerine-infusion pump-nurse scenario

In the ICU, a patient’s condition was deteriorating and multiple therapeutic interventions were being made at the same time. As part of this situation, five medication changes needed to be made immediately in order to reverse the patient’s condition. The nurse, receiving voice orders, was programming the infusion pump to administer one dose of nitroglycerine at 10 cm$^3$/h, and mcg/kg/min doses of four other medications. The patient experienced serious decrease in blood pressure a short while later as a result. Biomedical engineering stated that the pump was operating adequately yet noted that the dose of nitroglycerine programmed in was 10 mg/kg/min; they also noted that positioning of the pump in the patient’s room was awkward and not easily accessible from the front due to other critical care equipment being in the way. The attending physician stated that the intended dosage was clearly written in the record as being 10 cm$^3$/h.

References