In the ICU, an extensive array of variables from the hemodynamic monitoring display is routinely analyzed. However, the development of new display technologies is proceeding without adequate study of the monitoring tasks and behaviors of a primary user group—critical-care nurses. Semi-structured interviews focusing on the cognitive aspects of the hemodynamic monitoring task were conducted with 14 critical-care nurses. A systematic content analysis of qualitative data identified cognitive tasks that had applicability to the design of monitoring displays. The cognitive tasks of hemodynamic monitoring were (1) selective data acquisition, (2) applying meaning to the variables and understanding relationships between parameters, (3) controlling hemodynamics by titrating medications and intravenous fluids, and (4) monitoring complex trends of multiple interacting variables and patient response to interventions. Recommendations include designing the monitoring display to match the mental constructs and cognitive tasks of the user by applying conceptual meaning to the variables, highlighting relationships between variables, and presenting a “big picture” view of the patient’s condition. Monitoring displays must also present integrated trends that illustrate the dynamic relationship between interventions and patient response.

KEY WORDS
Critical care • Data display • Nursing • Task performance and analysis
because they instinctively “know” what to do. Others attempted to dissect this phenomenon and identified data-driven patterns that the expert recognizes in the situation, but cannot necessarily explain. However, in Aitken’s study, all but one of the nurses were able to consistently describe the rationale basis for their assessment. Furthermore, the nurse who described having a “gut feeling” was the only one to perform erratically. Thus, it appears that even when an expert nurse describes an intuitive feeling about the patient’s state, his/her assessment still depends on how hemodynamic data are perceived and his/her ability to interpret patterns in those data.

When gathering information for the purpose of designing a user interface, the focus can be on modeling the system or modeling the user’s behavior. System modeling succeeded in the domain of engineering with the application of abstraction hierarchy methods and the development of monitoring displays using principles of ecological interface design. In the ICU, the monitoring task is particularly complex since clinicians monitor a dynamic physiological system that does not necessarily respond within the normal constraints. Unlike engineered systems, the human body has individual variability that cannot always be predicted (for a general perspective on this issue, see Durso and Drews). Consequently, two patients with the same disease will not necessarily respond in the same manner. The physiological systems in the body also have the ability to compensate, although with severe disease or physiological exhaustion those compensatory mechanisms often fail. Furthermore, when critically ill or injured, or under the influence of medications that influence the cardiovascular system, physiological response may vary from day to day or minute to minute in the same patient. Hence, the constraints between variables in engineered systems that provide the basis for ecological interface design may not be as predictable in unstable physiological systems. Clearly, with our ability to consistently and predictably model the system being limited, to drive interface design a focus on the user’s behavior must be considered.

Hollnagel describes a functional approach to studying context-dependent human behavior that is more flexible than traditional information processing models. In this model of human action, the traditional end-point goal such as “achieving stability in the system” is replaced by a process-oriented goal such as “achieving stability as efficiently as possible.” Additional aspects of performance-related behavior include anticipation and planning. Using nursing practice as an example, it is recognized that there are many ways for a nurse to accomplish the control task of maintaining a patient’s blood pressure and cardiac output (CO) within a defined range through the use of medications and intravenous fluid administration. If there is a drop in the patient’s blood pressure, the nurse is expected to respond. However, what that response will be and what cognitive processes lead to that choice is difficult to predict. The nurse may also anticipate a certain course of events and will intervene before the patient’s condition demonstrates substantial changes. Goal parameters also change as a patient’s state worsens, and in some cases, the original goal is unattainable when a adverse effect of the chosen treatment causes injury to other organ systems.

To describe context-dependent human behavior, Hollnagel focuses on three components associated with human performance—competence, control, and constructs. In hemodynamic monitoring, competence is gained though education, training, and experience and can be evaluated though testing or observation. Practice standards are an attempt to raise competence by describing context-dependent procedures and defining minimum standards for monitoring and intervention. Part of the hemodynamic monitoring task also involves control, for example, responding to changes in patient state and predicting declines in patient status or adverse physiological events. A construct describes “the mental representations of what a person may know or assume about the situation in which the action takes place.” Nurses may use constructs to assess and understand the patient’s hemodynamic state and to make intervention decisions. They may also use constructs to predict the patient trajectory or response to treatment and to anticipate adverse events. One opportunity to affect nurse performance by supporting task-oriented constructs is to design display interfaces that promote data perception and support integration functions. However, it is unclear which constructs are most useful in the task of hemodynamic monitoring.

### RESEARCH OBJECTIVES

The goal of the present study was to acquire information about critical-care nurses’ monitoring practices by exploring, from a functional perspective, how nurses use monitoring displays and the cognitive tasks involved in their use. The findings were used to identify areas of improvement of hemodynamic monitoring displays to support the efficient monitoring behaviors. Finally, a number of recommendations for display design strategies were formulated.

### METHODS

#### Study Design and Procedures

An exploratory, descriptive design was used to capture the thoughts, perceptions, and cognitive processes of
each nurse participant. Individual, semistructured interviews lasting 30 to 45 minutes were conducted with 14 experienced critical-care nurses. Interviews were audio recorded and transcribed. The focus of the interview was on knowledge regarding current hemodynamic monitoring practices, use of technologies, and suggestions for designing new displays for patient monitoring. The structure of the questions was open ended to allow for follow-up probes to elicit further information. This study was approved by the University of Utah’s institutional review board, and written informed consent for conducting and recording the interviews was obtained from the participants.

Sample

Fourteen participants who met the following inclusion criteria were recruited: an active RN license, at least 3 years’ experience in critical care, currently working in an ICU, and familiarity with hemodynamic monitoring. Two of the nurse participants worked in a burn-trauma ICU, one was from a medical ICU, and the remaining 11 worked in a surgical ICU setting. All had current or recent clinical experience. Average experience in critical care was 11.6 (SD, 9.3) years (range, 3–30 years), and six of the 14 nurses were male.

Qualitative Data Analysis

This study uses a realist approach to analyzing the interview data wherein the descriptions are interpreted as the reality of the nurses’ monitoring practice and could be verified by observational study. Interview data were analyzed according to the guidelines for content analysis and theme development of Ryan and Bernard. In the first step of the data analysis, the transcripts were read several times to obtain a global overview of the interview data. General categories and themes associated with each interview questions were recorded. Emerging themes were use of global concepts in hemodynamic monitoring, applying meaning to the numerical data, how trend data are acquired and used, and how previous knowledge (and bias) affects variable selection.

Next, general concepts about nurses’ use of hemodynamic monitoring data were derived from the nursing literature on hemodynamic and other types of ICU patient monitoring. Themes that emerged from this review of the literature included use of limited data sets by expert nurses, structure of knowledge required for hemodynamic monitoring, use of intuition, holistic approaches to monitoring a complex system, nonlinear thinking, the relative value of clinical attributes, difficult concepts for novice nurses, complexity of the monitoring and decision-making task, and current use of technology. These themes were either merged with or added to the list that had been previously developed during the global reading.

With this preliminary list of themes, the interview data were reanalyzed, and individual statements were coded. Many themes derived from the nursing literature would have required an observation, and others such as the use of intuition did not emerge as a consistent approach to patient monitoring. As new themes emerged, previously analyzed data were reevaluated. After this process was completed, the coded data were examined to determine the structure and nature of the themes. At this point, the idea of these themes describing primarily cognitive tasks emerged, resulting in the final organizing framework.

Within each cognitive task, the data were examined again to identify statements made by nurse participants that were congruent or contradictory. Challenges and barriers were also identified and described. Lastly, the data coded under each category of cognitive task were then examined to determine the frequency of each response or comment. Since the nature of this study was purely exploratory, all comments and ideas presented by the nurses were treated with equal weight.

RESULTS AND DISCUSSION

An overview of the four categories of cognitive tasks identified during the analysis of the interview transcripts is presented in Table 1.

Task Category 1: Selective Data Acquisition

Nearly all interviewed nurses had a set of parameters in mind when they approached their hemodynamic monitoring task. Five of the surgical ICU nurses reported routine use of all the basic parameters obtained from a pulmonary artery (PA) catheter. As one nurse stated, “With the sickest patients, I’m pretty much using everything.” The other seven surgical ICU nurses appeared to focus on subsets of data, especially blood pressure, heart rate, and CO. These three hemodynamic parameters were routinely used to assess heart function and to monitor the patient’s postoperative recovery. In addition to variables obtained from a PA catheter, many nurses mentioned other sources of data central to hemodynamic monitoring: physical and cognitive assessment findings, urine output, and laboratory data.

Lack of perceived value and the fact that some parameters are not displayed on the main screen were two reasons given for the limited use of indexed variables.
such as the various ventricular work and vascular resistance indices. As one surgical ICU nurse explained, “The ones I focus on are the ones I see. I’m sure there’s some kind of function to [the indices] as far as the patient’s condition goes, but as far as monitoring our drugs, they are not that important.”

**ISSUES IN SELECTIVE DATA ACQUISITION**

When nurses use all of the data acquired from a PA catheter, they are integrating more than of eight hemodynamic variables with additional data obtained from the electrocardiogram, pulse oximeter, and ventilator display. Hemodynamic monitoring can justifiably be classified as a complex cognitive task. Complexity is heightened by interindividual variability related to prior health status, severity of disease or injury, and age.

Several nurses reported using a narrow range of variables. Since this study relied on subjective descriptions of the monitoring task, it is not clear whether these nurses routinely ignore other acquired variables or these are considered only when abnormal. The hemodynamic monitors also provide several indices located on secondary menus or screens that nurses do not routinely use. In some instances, the indices mentioned may not contribute any additional information to the hemodynamic picture; however, there may be key variables that novice nurses or nurses who do not routinely perform hemodynamic monitoring do not understand and therefore do not use.

**Task Category 2: Data Interpretation**

The interviews provided strong evidence that data interpretation is a central task during hemodynamic monitoring. Nurses used phrases such as “trying to put it all together,” “understanding or interpreting the numbers,” and “tying the numbers to the picture” to describe their cognitive activities. One nurse acknowledged that “critical-care nurses are in diagnosis mode.”

In response to being asked to identify difficulties that novices have interpreting hemodynamic data, one nurse stated, “They can look at a number, some can tell me the normal range, but then how it relates to a patient’s normal physiology is a difficult concept.” Rather than identifying one particular skill or variable, many nurses remarked that novices had difficulty integrating all of the numbers into a “big picture” representation of patient state. Upon further exploration, several key factors emerged as underlying barriers to constructing an overall appreciation of patient state. Four participants felt that new nurses miss potential problems by getting caught up in all of the numbers coming from the monitoring display. These nurses and almost all of the others reported that new nurses often struggle to apply meaning to the numbers. One stated, “The hardest part of this job is learning what the numbers mean and how you can project to avert a crisis.” It was generally felt that if the nurse could conceptualize what the variable represented and how it related to other variables, then they could understand how to use it. Three participants stated that new nurses have difficulty understanding the interdependence (or in some cases uncoupling) of variables. It was also remarked that new nurses have trouble linking changes as a series of cues to a developing problem. A new nurse may detect changes in a monitored variable, but may be unable to put the pieces of the puzzle together. Other nurses suggested that novices get caught up in the numbers, but do not know what to do with them. Another emerging theme was the negative impact of time pressure on the quality of patient monitoring. There is technology to acquire data, but in the end, as one nurse commented, “We have to be able to put it all together, and sometimes this doesn’t happen soon enough for the patient.”

**ISSUES IN DATA INTERPRETATION**

The monitoring task in the ICU goes beyond observation and documentation, although one nurse cautioned...
that physicians do not want nurses to be in “diagnosis mode.” Nevertheless, it was apparent from the interviews that critical-care nurses are frequently interpreting data for the purpose of identifying and understanding their patient’s pathophysiological condition.

Regardless of which term is used to describe the cognitive process, when utilizing data from the PA catheter, nurses are required to apply meaning to the variables to construct a picture of the patient’s hemodynamic condition. Understanding the interrelationships between the different variables is also an essential part of developing the mental model. The observations of experienced nurses were that novices have difficulty abstracting the big picture of the patient’s state or condition because they struggle to apply meaning to the numbers and have trouble recognizing the interdependence of variables. The novice may have a conceptual understanding of the acquired variables, but they often cannot conceptualize the underlying mechanisms pertaining to the patient’s hemodynamic state. Nurses who do not perform frequent hemodynamic monitoring may have similar problems with data interpretation.

**Task Category 3: Controlling Hemodynamics**

The most common uses of hemodynamic monitoring were vasoactive or inotropic infusion titration and intravenous fluid administration. All nurses reported that they were expected to titrate medications and fluids according to parameter-based medical orders or unit protocols. In one ICU, the nurses were also expected to initiate intravenous infusions based on unit protocols. As one nurse described the control task: “You’ve got to keep the wedge (PAWP) above 16, or you need to wean dobutamine to maintain a particular CO.” Another nurse remarked that novice nurses may understand the hemodynamics, but have trouble understanding how the infusions relate to what they are seeing on the monitor.

Several nurses described the task of understanding how the different medications affect the different hemodynamic variables. As one nurse stated, “We play the numbers game. If we have a high SVR [systemic vascular resistance] and low CI [cardiac index], then we give them something to reduce the afterload, which should raise the CI.” If the nurse attempted to treat the low CI independent of the elevated SVR, then they might induce worsening heart failure.

**ISSUES IN CONTROLLING HEMODYNAMICS**

Critical-care nurses use clinical data obtained from the monitors to drive treatment decisions. Most nurses expressed having an intervention in mind, such as medication infusion titration or fluid administration, while they assess parameters on monitoring display. Clearly, nurses develop a conceptualization of the patient’s status and condition to adjust treatments with the goal of achieving or maintaining homeostasis in the patient. The physiological goals in the ICU are multifocal, and many of the treatments induce secondary effects. Critical-care nurses are expected to anticipate the effect of treatment and may have to monitor for changes in other organs or systems. If adverse effects are detected, they are required to intervene again, perhaps with a new goal in mind.

**Task Category 4: Monitoring Complex Trends**

All nurses emphasized the importance of monitoring trends in critically ill, hemodynamically unstable patients. Despite this assertion, only one nurse used the monitoring display’s trending functions routinely. Other nurses reported knowing of only a few staff members who regularly examine computerized trends.

Several nurses stated that they primarily kept track of general trends in their head. As one nurse put it, “When I’m taking care of patients, I’m in the room all the time. I’m aware of what’s going on, so I don’t find [the trending functions] useful.” However, the handwritten flow sheet, it was explained, was the tool they consistently used for recording and monitoring trends. Even the sole nurse who used the monitor’s trending functions stated that, to fully evaluate trends, she deferred back to the flow sheet. Nurses verbalized that they were very reluctant to give up the handwritten record of trends, despite having computerized charting. The flow sheet was especially important as a tool for describing trends to the oncoming nurse during shift report.

Recording trends on a flow sheet involves writing down numerical values for each monitored parameter at specified intervals. This manner of monitoring trends in patient status has obvious drawbacks including the time required for data transfer, a lack of information between the times the data happened to be recorded, and the potential for errors in transcription. Given these problems, why do these nurses persist with the task of manually writing down values rather than use the computerized trending functions on the monitoring display? Obtaining answers to this question required an exploration of how these nurses use trending information and why current display technologies fail to meet their needs.

Whereas several nurses expressed interest in how a single hemodynamic variable such as CO changed over a 12- to 24-hour period, nearly all suggested that trends were most valuable in conjunction with a treatment goal. Two specific uses of goal-oriented trend monitoring emerged from the interview data. First, short-term trends were used to make decisions about future
treatment and interventions. Second, and most frequently, trends were used to monitor a patient's ongoing hemodynamic response to intravenous fluid and medication administration, often in the form of constant infusions that the nurse titrates. In addition, the nurse must communicate the patient's response to other members of the healthcare team. As one nurse stated, “Our monitors store all of the information, but not in a meaningful way. It's really important for an ICU nurse to be able to see everything at once.”

A nurse who worked as an educator in a burn-trauma ICU hypothesized about another reason for the limited use of available trending functions. “Most ICU nurses know how to evaluate their patient and know what’s going on with them at that moment. Whatever happened in the past is not at the forefront of their mind.” Despite rating trend monitoring as a highly useful tool, nurses tend to focus on the patient's present state.

**ISSUES IN MONITORING COMPLEX TRENDS**

The majority of participants were not using available computerized trending functions. One of the primary limitations of computerized trending functions is that they do not show the interrelationships between monitored variables and interventions. The ICU nurse wants to be able to easily observe the patient's hemodynamic response to the titration of a particular drug or an adjustment of the ventilator setting. Charting and monitoring trends on a flow sheet are time consuming and incomplete. Furthermore, errors may occur during the manual transfer of data. In addition, it is important for the entire healthcare team to have access to trending information.

Another concern was the primary focus of some nurses on the present situation, with limited evaluation of trends. Although an understanding of a patient's current status is crucial, many conditions evolve over time (eg, sepsis and heart failure). A seemingly stable patient, when only current data are evaluated, may show signs of a developing condition if trends are closely evaluated. Because trending data are not easily accessible or relevant to their task in its current form, critical-care nurses may be missing an important element of ICU monitoring.

**RECOMMENDATIONS FOR NEW DISPLAY DESIGN STRATEGIES**

It appears that critical-care nurses use mental models to understand the state of the patient and to predict the patient's trajectory or response to treatment and to anticipate adverse events. One opportunity to affect nurse performance lies in the development of constructs by designing display interfaces that promote data perception and data interpretation. One of these constructs involves trying to apply a conceptual meaning to the variables. Another is the need to understand what some nurses described as the big picture. This global perspective involved the incorporation of the relevant parameters, combined with information concerning the patient's history and current treatment regimens. It appears that if a nurse cannot conceptualize the meaning of a parameter or see the big picture, then the data will go unused. The hemodynamic monitoring display should also attempt to highlight relationships between associated variables. Under conditions of normal homeostasis, relationships between physiological variables can be accurately modeled. However, with severe disease or injury, it is difficult to predict the physiological systems' ability to respond since in many cases compensatory mechanisms are overwhelmed or nonfunctional. In addition, the body's physiological mechanisms are influenced by medications and other treatments, such as the mechanical ventilator and aortic balloon pump. Finally, since time pressures are common in the ICU, clinical data must also be presented in a manner that promotes rapid perception and, more importantly, rapid data interpretation.

These findings support the development of integrated graphical displays by depicting variables as shapes that visually resemble and behave in a similar manner to the physiological system. These graphical displays may help nurses see the big-picture view of a patient status, thus reducing the amount of data processing they are required to perform during emergent events when time pressures and other tasks limit the resources available for step-by-step numerical data interpretation. Graphical displays may also help novice nurses learn about relationships between constrained hemodynamic variables and develop an understanding of the links between treatments and the range of possible hemodynamic responses. However, the method of graphically representing variables and relationships between variables should be thoroughly tested among diverse groups of critical-care nurses to ensure that the data can be correctly interpreted.

One challenge of developing integrated graphical displays for monitoring physiological systems is that constraints are often difficult to accurately model. Therefore, the goal of these displays should be to provide cues to the relationships between associated variables, rather than attempting to portray constraints as is done in the ecological interface design of engineered systems theorized by Vicente and Rasmussen. Reasons for the limitation of this approach are provided by Durso and Drews, with one of the main problems being the differences in principle between monitoring technical and natural systems that lead to different constraints and requirements.
Display interfaces for critical-care nurses must be designed to support active decision making rather than simply providing an indication of the patient’s status. A monitoring display should present the data in the context of the control tasks of the critical-care nurse. In critical-care nursing practice, hemodynamic monitoring is primarily used to titrate medications that affect the cardiovascular system or to administer intravenous fluids. Monitoring displays therefore should provide a way for nurses to rapidly perceive the patient’s volume status and provide support for the control task of titrating vasoactive medications.

The present study demonstrated that critical thinking is central to all aspects of monitoring task. The goal of the monitoring display is not necessarily to provide the nurse with a solution to the problem. Rather, the display should highlight changes in patient status that may be missed because of a lack of vigilance or inexperience and provide contextual support for data interpretation, decision making, and monitoring the treatments that are implemented. Finally, it is important to emphasize that any automation may create a situation that leads to deskilling of the involved personnel.

When monitoring critically ill, hemodynamically unstable patients, nurses need a data presentation that explicitly shows the relationship between treatments and physiological changes over time. However, the issue of monitoring complex trends in a critically ill patient’s hemodynamic state has not been a major focus of patient monitoring research and technology development. Computerized trending functions on monitoring displays appear not to be routinely used because they do not provide the integrated, response-to-treatment trends that critical care nurses require. New trend displays must show the relationships between key hemodynamic variables and treatments such as medication and fluid administration, intravenous infusion titration, or ventilator adjustments. Automation of trending information could reduce the risk of human error in the transfer of data, significantly decrease the time a nurse spends charting, and would provide a continuous display of trended variables. Nurses should also be able to use a summary of trending information to enhance communication with other healthcare team members and during handoffs such as the change of shift report.

CONCLUSION

To date, myriad monitoring displays and other display interfaces have been developed without a thorough examination of nurses’ mental model of the task or behavior that the interface is designed to support.

The dynamics of monitoring a physiological system make it impractical to use traditional approaches to monitoring display design such as the abstraction hierarchy methods outlined by Vicente and Rasmussen. Using an information-processing approach to behavior modeling is also limited since nurses are highly proactive and adaptive in their approach to patient monitoring. This study used a functional approach to behavioral modeling as described by Hollnagel to describe the cognitive tasks that critical-care nurses undertake during hemodynamic monitoring of severely ill and injured patients. This approach allows investigators to gather data regarding global behaviors, rather than focusing on individual incidents, the variety of which is infinite. The primary goal of the tasks described in this study was to achieve physiological stability in the patient as efficiently as possible. Knowledge of these context-dependent tasks can then guide the designers of patient monitoring displays to best support nurses’ need to be proactive and adaptive in the most efficient manner with minimal error.

New display technologies must be developed with attention to the specific cognitive tasks of the intended user group. Nurses have a distinct focus in their approach to patient monitoring that may differ from that of physicians, technicians, and other critical-care clinicians. Without rigorous evaluation of these underlying differences, features designed specifically for one domain may not support the tasks of other users. Since nurses perform the vast majority of patient monitoring in the ICU, display technologies must support the cognitive tasks of this particular user group to ensure that technology does not become a source of error and a threat to patient safety.

REFERENCES