Collaborative Prototyping Approaches for ICU Decision Aid Design

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Abstract

When computer-based aids do not support the human users’ decision-making strategies or anticipate the organizational impacts of technological change, advances in information technology may degrade rather than enhance decision-making performance. Such failures suggest the design of human-computer cooperation for problem solving and decision-making must be driven by human cognitive and organizational process requirements rather than computer technology. Decision- and user-centered development techniques involve domain experts and end-users in the earliest phases of design to evolve an understanding of requirements through iterative prototyping. This paper presents a collaborative approach to cognitive systems engineering applied to developing a clinical aid to assist respiratory care in the surgical ICU.

1. Introduction

Information presentation and interaction designs for computer-based decision aids play an integral role in determining the performance integrity of the delivered system. Computer-supported human decision-making performance in critical situations is dramatically affected by the design factors addressing:

- user-computer cooperation - task allocation, information sharing requirements;
- environmental characteristics - complexity, uncertainty, and dynamics; and
- situational response requirements - timing and precision.

Mismatches in the system design involving these factors result in the ineffective use of resources and, in the worst cases, disastrous system errors and failures. Woods and Roth¹ cite several cases where automation degraded rather than improved performance when designers did not support the human users’ decision-making strategies and failed to anticipate the organizational impacts of technological change. Such failures suggest the design of human-computer cooperation for problem solving and decision-making must be driven by human cognitive and organizational process requirements rather than computer technology.

The surgical intensive care unit (SICU) is one of the most information-intensive environments in modern medicine. The SICU “decision system” comprises the not only an array of medical information technology resources for sensing and reporting patient data, but also the clinical staff who collaborate to monitor and interpret clinical data to make judgments about patient status and decisions about patient care. Moreover, this decision system is a highly mutable construct, adapting both the human expertise and the medical technology applied to best address the needs of a specific patient. This flexibility further increases the difficulties in designing acceptable computer-based decision aids. Decision- and user-centered development techniques involve domain experts and end-users in the earliest phases of design to evolve an understanding of requirements through iterative prototyping. This paper presents a collaborative approach to cognitive systems engineering applied to developing a clinical aid to assist respiratory care in the surgical ICU.

2. Designing to Aid Clinical Decision Makers

2.1 Foundation Concepts

Errors in and mismanagement of medical care manifest as a result of inadequacies in the design or integration of medical devices, unproductive or inappropriate organizational policies, human cognitive errors (due to stress, fatigue, or information overload), situational factors (crowding and clutter), and environmental factors (extreme weather, power failures).² Klein’s Naturalistic Decision-making (NDM) model³ of expert decision-making in time-stressed, high-threat situations proposes that experts recognize similarities in situations to events previously experienced. This recognition triggers candidate courses of action for mental simulation to assess their suitability in the current situation. Empirical studies with nurses in the NICU support recognition-primed decision-making model.⁴ In complex decision domains, mentally simulating the causal chain of decision consequences can exceed human short-term memory...
capacity. Coping strategies to minimize the increased cognitive load may result in a failure to anticipate unacceptable side effects.\textsuperscript{5,6}

The effective introduction and integration of new technology into an existing decision system requires user participation in design and an interdisciplinary collaboration for iterative development. The discipline of systems engineering necessarily crosses disciplinary boundaries. In addition, the management, cognitive, and behavioral sciences include many advocates for holistic approaches to understanding the multiple facets of organizational decision making. These cross-cut concepts such as:

- \textit{Training \\ \\ Learning} - situated learning,\textsuperscript{7} learning organizations & knowledge management,\textsuperscript{8,9}
- \textit{Process Modeling \\ \\ Improvement} - process re-engineering\textsuperscript{10} and IT-enabled change;\textsuperscript{11}
- \textit{Cognitive Systems Engineering} - user-centered and decision-centered design,\textsuperscript{12,13,14} collaboration support and situated design.\textsuperscript{15} These approaches model humans and technology support in organizations as “organic” to information processing, knowledge-creating, and decision-making processes.

Woods and Roth\textsuperscript{1} use the term \textit{cognitive systems} to describe the teaming of a human user and machine to perform problem solving tasks. Cognitive systems engineering (CSE) applies multi-disciplinary research findings and design experience from the cognitive science and engineering disciplines to the design, evaluation, and construction of systems supporting and improving human task performance.\textsuperscript{16} The CSE emphasis on supporting the needs of the decision-maker represents requirements-driven design. The resulting system should demonstrate consistently high human-computer decision task performance as determined by appropriate measures of performance and effectiveness. To incorporate these concepts requires CSE design methods that guide the matching of user, task, and organizational, situational and environmental requirements to available tools and techniques for the design of human-machine cooperative decision-making.

\section*{2.2 CSE Development Approach}

The identification and analysis of decision-aiding requirements and the design of human-computer cooperative systems to address those requirements involves creating and refining multiple models. These models encompass various aspects of the problem domain and evolving technological solutions. System requirements documents contain text and graphic models of the operational need; software and hardware designs present text and diagrammatic models of the solution path proposed. Prototypes are also models, representing the current design of the system being developed. In between are many more models created in data structures, drawings, charts and other forms. Structuring, evaluating and refining these models highlights gaps in the requirements or design and alerts the designer/developer to the critical factors for successful performance.

In evolutionary design and development processes, prototyping has become an important tool for identifying user requirements and providing feedback on the working design against the requirements.\textsuperscript{17,18} Ehrhart\textsuperscript{16} outlines a CSE framework for capturing and evolving decision support requirements through iterative prototyping. Design guidance tables synthesize research from software engineering, decision sciences, cognitive psychology and other related fields to assist the designer in defining a more robust set system requirements and guide design tradeoff decisions. This framework provides a guide to creating, structuring, and applying a series of models to designs for human-machine cooperative problem solving.

Initial problem definition examines three general types of information:

- System Context - who will use the system, what they need to do with it, and the situated conditions of use.
- Constraints - “built in” requirements for inputs, outputs, interconnection, and environmental tolerances.
- Technological Opportunities - leverage points where technology may yield greatest benefit.

To understand the system context, the design team gathers information to understand the functional goals of the system and develop a profile of the system requirements as defined by:

- users - experience, training, roles;
- tasks - high-level functions, performance goals, timing, criticality;
- organizational context - goals, missions, control structures, communication modes;
- environment - when, where, how, and under what conditions will the system be used.

This information comprises the operational need the new system must meet. The various dimensions of the system context each generate constraints on the system that must be explored during the requirements phase and addressed in the design. Moreover, constraints involving human performance, hardware, and software interact. For this reason, it is essential that
the design team include domain experts with experience as decision-makers in the target environment.

Iterative prototyping exposes small samples of prospective users and/or designers to a succession of evaluation protocols using simple models, storyboards, and/or interactive prototypes. Prototype evaluation uses qualitative methods such as expert walkthroughs, questionnaires, structured and informal interviews, focus group analyses, heuristic inspections, and verbal probes/protocols. Used from the earliest stages of design, walkthroughs elicit and review domain models, elaborate decision task protocols, validate designs, and verify systems. Paper prototypes aid in eliciting domain/task knowledge and support early, inexpensive review of information presentation and interaction designs to prevent costly rework. Verbal probes and protocols employed during task performance help explore the decision-maker’s cognitive models and processes. In the formative phases of design, these methods aid in capturing system requirements, user domain and task models, and potential error sources. Although not rigorous, these methods are highly effective in locating usability and design assumption errors. This formative evaluation continues through the iteration of a succession of computer-based prototypes to confirm the satisfactory addressing of the users’ requirements and guide the subsequent revision of the system.

3. Application Example: Supporting Diagnostic Reasoning in Respiratory Intensive Care

Decisions in the SICU are often critical and urgent; at the same time, there is increasing pressure to reduce the time an individual is under intensive care and there are an increasing number of patients requiring such care. The pressures of information overload and reduced decision time suggest the value of a computer-based clinical assistant that provides:

- graphical visualization of clinical data to communicate essential information quickly;
- decision-focused information integration for enhanced understanding; and
- simulation to permit examination of alternative therapies through “virtual trials.”

To address these goals, researchers in the Center for Anesthesia Research Center at the University of Pennsylvania assembled an interdisciplinary team to collaborate in developing a decision aid (the VQ/PQ Assistant) to support clinicians in respiratory care.  

3.1 Respiratory Care in the SICU

Certain fundamental concepts in respiratory care, such as the three-compartment model for gas exchange and the pressure/volume relationships for lung ventilation, are approximately quantitated in every patient as a conceptual representation of pathophysiology. Others, such as pulmonary vascular pressure/flow relationships or effects of the distribution of ventilation/perfusion ratios, are understood in theory but seldom used diagnostically because they are technically difficult to measure or approximate. Currently available commercial clinical information systems collect information from the bedside monitors as well as from the pharmacy, pathology, microbiology and radiology departments so that essentially the entire patient’s chart could be accessed via the computer interface.

Early systems for respiratory intensive care supported evaluating pulmonary function tests or providing smart alarms for malfunctions. Variations of these systems with improved data collection, display and calculation of physiological variables led to monitoring devices of the type now found in all intensive care units. Later attempts to develop computer-based physician assistants focused on well-defined decisions, but the systems were often hard to use or applicable to only a limited set of problems. As a result, research interest shifted from providing assistance to providing advice to the physician for diagnosis and therapy.

Projects such as VentSim resulted in impressive developments in intelligent aids. Nevertheless, even in the most sophisticated of these systems, the pathophysiology of cardiopulmonary function encompassed is less advanced than that of an intensivist and none of the systems have been adopted clinically. Heathfield and Wyatt attribute the poor acceptance rate of computer-based medical management advisory systems to inadequate attention to the needs of the clinical end-users. To avoid similar failures, the V/Q-P/Q Assistant project adopted a user-focused design approach intended to meet the specific needs of the SICU medical and nursing staff.

The integrated pulmonary pathophysiology model (V/Q-P/Q Model), derived from two separate but well-established concepts: gas exchange represented in the ventilation/perfusion ratio distribution; and the characterization of the pulmonary vascular bed using an actively controlled and passively modulated pressure/flow curve. While clinicians and pathophysiologists recognize interrelation of gas exchange and blood flow distribution, the V/Q-P/Q Model permitted these interactions to be quantitated for the first time to provide predictions for research in therapeutic techniques.

To extend therapeutic support to critical care environments, the V/Q-P/Q Model needed to be em-
bedded in clinical support system with an interface that aided intensivists in judging relative benefits of therapeutic options. The V/Q-P/Q Assistant seeks to enable medical staff (physicians, nurses and others) to arrive at decisions more efficiently by providing easier access to accumulated data, improved analysis of the pathophysiology, and the ability to simulate the responses of a specific patient to therapeutic trials (virtual therapy). The initial prototype focuses only on data displays that assist in the evaluation of cardio-pulmonary function. The system combines conventional clinical methods with both ventilation/perfusion ratio distributions and pulmonary vascular pressure/flow relations, integrated into the V/Q-P/Q Model.35,19

3.2 Designing the VQ/PQ Assistant

The personnel needed for implementation of the V/Q-P/Q Assistant represented four interdependent design components:

- problem domain - SICU decision maker’s requirements and the knowledge base for the pathophysiologic derivations;
- user interaction development - form, feel and effectiveness of the human-computer interface;
- interface software development;
- evaluation of designs and user performance.

Each of these areas required different expertise and experience in the design team. Moreover, each team member had to develop a working understanding of the other areas to promote collaboration.

The prototyping process began with an initial set of assumptions about the system requirements. An opinion survey of SICU physicians revealed five principal medical events encountered: ventilatory inadequacy, need for circulatory assistance, adult respiratory distress syndrome (ARDS), impaired pulmonary blood flow and cardiac failure. A physician modeled a systematic (entity-relationship diagram) approach to cardiopulmonary decision making based on the data available in the SICU. This model was then refined by expert walkthroughs with two other physicians to reach an initial consensus about what data is required most frequently, how it should be ordered, what time trends and level of detail should be available and what additional information would be particularly desirable.

These results defined the initial design requirements for the sources of information and the human-computer interface. This preliminary analysis was extended through observation, knowledge elicitation, and structured interviews. Even the choices of hard-

ware and software were governed in part by the constraints expressed by the physicians that the computation must be fast, the configuration of the displays rich, the equipment unobtrusive, the database access flexible and storage space considerable.

Feedback for rapid prototyping uses design reviews with small numbers (2-5) of subjects. Formative evaluation methods employ qualitative methods for identifying and validating system requirements and software designs with domain experts and software developers. Generally a mixture of these methods is required, including expert walkthroughs, paper-prototyping, focus group analysis, think-aloud protocols, post-test debriefings, ad opinion surveys.

The initial cognitive walkthroughs with clinicians provided feedback to the design process through decision-focused reviews of the prototyped design. To capture a range of experience, the review group drew from a cross-section of physicians, clinicians, and nursing trainees. The initial reviews used ventilatory support weaning scenarios to explore the effectiveness and usability of the graphical display. Three paper storyboards illustrated a successful weaning, a weaning failure, and an ambiguous, respectively. Reviews covered:

- Information integration & presentation – are diagnostic cues presented correctly? What are the alternative configurations?
- Emergent information – what information emerges in the configuration of patient data? Does this improve decision making?
- Possible error sources – what aspects of the design confuse or mislead?
- Usability – what are the subjective reactions to the aid? How easy is it to use?

Feedback from these informal reviews guided significant redesign of the system concept before system programming began. The reviews also served to prototype the instruments and protocols for the formative evaluations to be conducted in the future. Early expert reviews saved time and effort in expensive rework. More important perhaps, the process jointly engaged the creative minds of medical experts and technologists explore the possibilities for improving patient care at the bedside.

4. Conclusions

As technologists, our paradigm is often: build it, test it, and train them to use it. This paradigm fails when new technology effects dramatic changes in the decision system. Introducing advanced decision support technology into complex, dynamic decision environments via multiple, interdependent information
systems demands an understanding of concurrent changes in technology requirements, in organizational processes, and in learning required to improve organizational capability. Innovative design involves creative discovery and collaboration environment that fosters exploration. The target users must be involved in the design of evolving systems to discover the best applications of those systems in a changing environment and provide feedback on emerging requirements to system developers.

Acknowledgements

Research reported in this paper was supported in part by NIH LM05997 and the Center for Anesthesia Research, Hospital of the University of Pennsylvania.

References