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Using Cognitive Work Analysis to Design Clinical Displays

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Abstract

In today's ICUs clinicians routinely integrate huge numbers of discrete data points to arrive at a coherent picture of their patients' status. Often the clinician must obtain those data elements from many devices, which makes the problem more difficult. Because presenting data visually amplifies cognition by capitalizing on well-known human perceptual capabilities, it is not surprising that a growing body of research is directed at the effective presentation of visual information in clinical displays. However, developing clinical displays that effectively support clinicians' integration and understanding of many discrete data elements in complex, high technology work domains such as ICUs remains elusive. It may be that traditional analysis and design methods simply are inadequate for this kind of complex environment. Vicente has described a new methodology, called "cognitive work analysis" (CWA), which is targeted at the analysis of complex work domains. The analysis differs from traditional analytic methods in significant ways, particularly in its primary focus on analysis of the work domain, but also in its prescription for explicitly collecting information at five levels (the work domain, diagnostic and treatment tasks, diagnostic strategies, socio-organizational, and clinician skills) that place constraints on the ultimate display design. In this model, the order of data collection is also crucial. Because the work domain constraints tend to be the most permanent, they are likely to have the most impact on design, and so analysis starts there. As the analysis proceeds through the subsequent levels, additional design constraints are identified. We recently used CWA to analyze the information needs for interactive graphical displays that will integrate and represent data in structures that help clinicians visualize a patient's physiological status. We found that the analysis was an effective way to identify information needs at multiple levels. Based on our experience, CWA is a generic methodology that is highly applicable to medical informatics.

Keywords:

Analysis; Display Design; Cognitive Work Analysis

Introduction

Today's ICUs are complex, high technology work domains in which clinicians routinely integrate huge numbers of discrete data points to arrive at a coherent picture of their patients' status. [1-3] Somehow clinicians must distinguish those data points that are relevant from those that are irrelevant in a particular situation, [4] what has been called the "significance of data" problem. [5] But clinicians cannot synthesize that much information and predict accurately the outcomes of various treatment options. The complexity of healthcare exceeds the capacity of the unaided human mind. [6]

Today's physiological monitoring systems do not make the clinician's task easy. Not only are many data elements needed, but also the clinician must obtain those data elements from many devices. [7,8] This induces sequential, piecemeal form data gathering" [5] that "precludes an organized, coherent understanding of the interrelationships of cardiac, pulmonary and tissue perfusion functions and their underlying physiologic mechanisms." [9, p. 47]

Can Technology Help?

Designers have long recognized that presenting data visually amplifies cognition by:

- transferring some of the cognitive processing effort required for text processing to parallel perceptual processing mechanisms,
- integrating data so less memory search is required,
- capitalizing on well-known human pattern recognition and perceptual inference capabilities,
- developing the visualizations in a medium which can be manipulated .[10]

For these reasons, a growing body of research is directed at the effective presentation of visual information in displays. For example, Weinger et al. evaluated a display in which variables were shown as histograms. [11] When all variables were in normal range, the display showed a normal "horizon." Subjects detected changes 15% faster with the horizon display than with numerical displays. When a similar histogram-type display was used to develop a critical care workstation, deviations from normal were detected rapidly. [12] Other designers have shown the various dimensions of a problem as part of a single physical object. Cole and Stewart developed a metaphor graphic in which they represented ventilation as a rectangle where the width of the rectangle revealed respiratory rate and the height of the rectangle revealed tidal volume. [13] When normal, the rectangle approximated a square. Other medical examples include modeling of physiological patterns as circular diagrams, "hemodynamograms," [14] and the Aberdeen polygon.[2] Despite the effectiveness of these displays, developing clinical displays that effectively support clinicians' integration and understanding of many discrete data elements in complex, high technology work domains such as ICUs remains elusive. "We have yet to find the optimal method of displaying these data" .[15, p. 876]

An Alternative Approach: Ecological Interface Design

Ecological interface design (EID) was first described by Vicente and Rasmussen. [16] EID [16-18] integrates aspects of ecological psychology theory [19,20] and cognitive engineering. [21] In a seminal study, Vicente used Rasmussen's abstraction-decomposition hierarchy [22] to identify relevant work-domain constraints in a thermal-hydraulic process control microworld that was designed to be representative of industrial process control systems. A mimic display provided the visual context for the microworld. One of the crucial and novel aspects of the design was Vicente's mapping of the identified work domain constraints onto the geometry of the interface as perceptually salient objects. In initial laboratory experiments with static displays, Vicente found that the EID enhancements improved users' fault detection and diagnosis; in later interactive experiments, system control was also found to be improved. [17,23] Because a significant amount of domain knowledge was transferred to the interface, users were less dependent on memory for recalling or calculating crucial relationships among data elements and instead were able to use their powerful perceptual capabilities to recognize critical events and goal-relevant relationships. Recently, EID principles have been used successfully as a basis for designing several medical applications. [24-26]

Cognitive Work Analysis

Vicente has described how an alternative approach to analysis, Cognitive Work Analysis, supports ecological interface design for complex domains. [17] A cognitive work analysis has five levels (Fig. 1). In contrast to traditional methods that begin with the user's model of the problem, [27] cognitive work analysis begins by describing the work domain. This identifies the most permanent constraints on the problem. Analysis then progresses to a task analysis, followed by a diagnostic strategy analysis, a social-organizational analysis, and finally a user skill analysis. As additional constraints are defined at successive levels (tasks, strategies, etc.), design options become increasingly clear. The remaining degrees of freedom in the design are those needed to give the knowledgeable user sufficient flexibility to cope with unanticipated problems. The methodology has been applied successfully to the development of complex technology for applications as diverse as libraries and nuclear reactors.

WORK DOMAIN: Hemodynamic Management

TASKS: Recognition, Diagnosis, Treatment

STRATEGIES: Diagnostic, Treatment

SOCIAL-ORGANIZATIONAL

CLINICIAN SKILLS

Figure 1 – The five levels of constraint in a Cognitive Work Analysis [17], as applied to hemodynamic management

Cognitive work analysis begins by identifying the constraints in the environment (i.e., the work domain) that are relevant to the operator and to system goals. [17] One tool for accomplishing this is Rasmussen's abstraction-decomposition hierarchy, which describes the work domain along two dimensions: part-whole and means-ends. [22] The part-whole decomposition looks, for example, at the body from cell to whole body. In the means-end abstraction, the same human body system can be described at different levels (e.g., as *purposes, balances, processes, physiology*, and *anatomy*). [28] Requirements for proper system functioning at one level appear as constraints on lower levels. For example, the body's goal of maintaining adequate tissue oxygen (a *purpose*) acts as a constraint on circulation and oxygenation *processes.*

Ultimately, the goal of EID is to make those identified work domain constraints visible in the interface. To accomplish this, designers first represent each relevant process variable with a distinct display element, then organize those display elements so that symmetries that arise from their interaction correspond to high-level process constraints. Finally, designers nest the symmetries of the display in ways that reflect the hierarchical structure of the process.[29]

We are currently conducting research to facilitate clinicians' decision making through ecologically designed interactive graphical displays that integrate and represent data in structures that will help clinicians visualize a patient's physiological status. In the following section, we describe our application of cognitive work analysis to identify the information needed for the displays.

Methodology: Cognitive Work Analysis

Following Vicente's cognitive work analysis methodology, [17] we identified technological and organizational design requirements at five levels:

Work domain analysis

We began with an abstract-decomposition model of the cardiovascular system done by Hajdukiewicz for an operating room environment. [28] That analysis had shown differences in the portions of the model (that is, information structure) used by surgeons and anesthesiologists. Therefore, we anticipated the need for a somewhat different analytic model for dealing with hemodynamic decisions in ICUs. For that reason, we modified the Hajdukiewicz analysis, based on our own literature review and discussions with expert ICU clinicians, to create an analytic model specific to hemodynamic management. Surprisingly, our experts began at the cellular level of analysis, by assessing the cellular oxygenation status. That was not at all what the analysts on the team expected and was contrary to Hajdukiewicz's analysis with clinicians in another specialty.

Identification, diagnostic and treatment task analysis

We used Rasmussen's decision ladder [30] to describe the decision making of expert clinicians and the informational support needed at each step as they used worksheets with actual patient data to make decisions about clinical problems and possible treatment. The decision ladder proved to be an efficient way to capture the information used by clinicians, the level of analysis at which the information occurred and the temporal order of the search process. The result was a goal-relevant subset of work domain data to be used in the decision support display that included four levels of Rasmussen's hierarchy: purposes, balances, processes, and physiology (Fig. 2). [21] One of the interesting results was that although surgeons work at the anatomical level, ICU physicians (intensivists) and ICU nurses typically do not. Although our initial emphasis will be on displays to support problem recognition and diagnosis, we could not ignore treatment altogether because treatment efficiency is one of our design goals. Consequently, we have begun to identify treatment algorithms that might be supported by a hemodynamic management display (Fig. 3). It is significant that treatment options are targeted at the physiology level of the oxygenation model.

Diagnostic strategies analysis

The strategies analysis is a natural follow-up to the task analysis, because Rasmussen's decision tool allows analysis of decision makers' strategies as the clinician solves actual clinical problems. In our previous research, we identified four predominant strategies that conformed to those described by Rasmussen and Jensen: topographic search, pattern recognition, decision table, and hypothesis and test. [31] In topographic search, the clinician refers to a model of normal physiology, either memorized or as a diagram. In pattern recognition, the individual recognizes a particular pattern of data as signifying a particular patient state [15]. Decision tables are a series of "if-then" rules; for example, if cardiac output is decreased and preload is high, consider administering vasodilators or diuretics. Finally, hypothesis generation and testing begins with a clinician's hypothesis about the patient's state that is then tested using a functional model. In our current analysis, hypothesis testing, pattern recognition and decision tables were most frequently observed. Taken together with the findings in our previous studies, this suggests that an effective display must support at least the three strategies, if not all four. Given the planned visual nature of the display, it seems likely that the display may encourage more topographic search than the current worksheet.

Social-organizational analysis

For this part of the analysis we used direct observation, but with the assistance of an expert clinician. We were reminded that in ICUs, physiological monitors are routinely watched by nurses and only rarely by physicians. Nurses assess the accuracy of the monitored data before recording values on flowsheets and titrate drug therapy to maintain patient parameters within targeted ranges. Physicians make diagnostic and treatment decisions based on synthesis of data collected on flowsheets or in the patient record. This part of the analysis somewhat changed our view of the design project. It became increasingly clear that our integrated decision support display would replace, not the monitors, but the paper worksheet

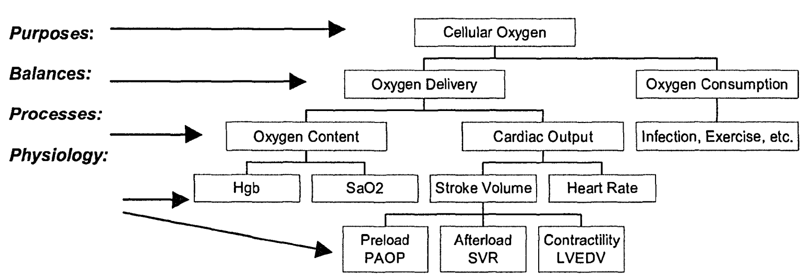

Figure 2 – The information needed for a hemodynamic decision support display

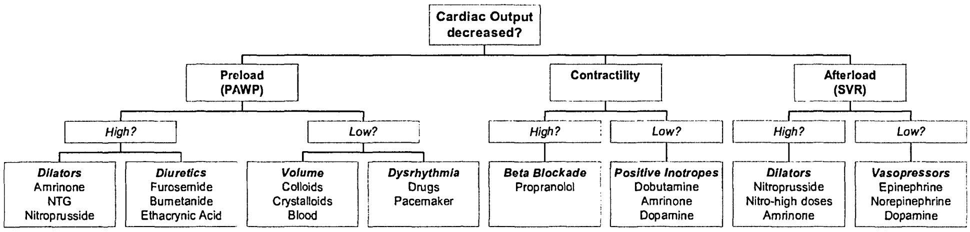

Figure 3 - A treatment algorithm for decreased cardiac output

(or in some agencies, the computerized worksheet), for it was from the data compiled on that sheet that diagnostic and treatment decisions were made.

Clinician skills analysis

ICUs increasingly are staffed by relatively inexperienced personnel. In teaching hospitals, such as ours, residents are the primary decision makers along with nurses who, because of the current shortage, may be quite inexperienced. Expert clinicians are able to quickly hone in on the key data elements on a worksheet to make decisions about their patient's status. In contrast, novices tend to consider each data element as equally important and are likely to consider each in order, top to bottom. Worksheets are organized to facilitate data entry; data elements from a particular information source (monitor, etc.) are organized together. Unfortunately, this is not the best way to support clinicians' decision making. Novice ICU residents and nurses need more decision making support than expert clinicians; but an effective display should support both groups by allowing shortcuts or by incorporating useful, accurate models and algorithms. In addition to reviewing literature on problems in the interpretation of physiological data, we used retrospective chart reviews to identify specific areas in which displays might be used to improve clinicians' decision making.

The Results: A Prototype Display

Based on this analysis and our previous work, we developed a concept design for a decision support display for hemodynamic management that presents information at four levels: The *purpose* of therapy is to maintain adequate cellular oxygenation. If oxygenation is inadequate for needs, the clinician then evaluates the *balance* between oxygen delivery and oxygen consumption. Depending on which side is out of balance, the clinician would look for the source of the problem in either oxygen delivery or metabolic *processes* and their underlying *physiology*. If oxygen consumption is the issue, the clinician is prompted to consider moderators of cell metabolism.

Conclusion and Implications

The cognitive work analysis we followed proved to be extremely useful for identifying the constraints on a decision support display for the intensive care environment. It was helpful to have Hajdukiewicz's work domain analysis as a starting point, although there were differences in how ICU and operating room clinicians view the cardiovascular system. For that reason, one work domain analysis cannot be used for all clinical specialties, despite its common physiological basis. Although Rasmussen's tools for analysis of the work, task and strategies domain proved to be particularly helpful, there are no specific tools for the other two domains. However, these are areas that researchers in cognitive science, medical informatics, and human factors research have emphasized for some time. Consequently, there are many useful tools and techniques available on which the analyst can draw. In conclusion, Cognitive Work Analysis is a technique that can be as useful in healthcare as it has been in other complex domains. It is a very general approach that seems likely to facilitate analysis in very many domains, but that remains to be shown in further research.

References

[1] East TD, Wallace J, Morris AH, Gardner RM, Westenskow DR (1995). Computers in critical care. *Crit Care Nurs Clin N Am* 1995: 7(2): 203-217.

[2] Green CA, Logie RH, Gilhooly KJ, Ross DG, Ronald A. Aberdeen polygons: Computer displays of physiological profiles for intensive care. *Ergonom* 1996: 39(3): 412-428.

[3] Saba V, McCormick K. *Essentials of Computers for Nurses*. Philadelphia: Lippincott, 1986.

[4] Groen GJ, Patel VL. The relation between comprehension and reasoning in medical expertise. In Chi MTH, Glaser R, Farr MJ, eds. *The Nature of Expertise*. Hillsdale, NJ: Erlbaum , 1988; pp. 287-310.

[5] Woods DD. Paradigms for intelligent decision support. In Hollnagel E, Mancini G, Woods DD, eds. *Intelligent Decision Support in Process Environments*. Berlin: Springer-Verlag, 1986; pp. 153-173.

[6] Eddy DM. Practice policies: Where do they come from? *JAMA* 1990: 263: 1265, 1269.

[7] Donchin Y, Gopher D, Olin M, Badihi Y, Biesky M, Sprung, CL, Pizov R, Cotev, S. A look into the nature and causes of human errors in the intensive care unit. *Crit Care Med* 1995: 23(2): 294-300.

[8] Stafford TJ. Whither monitoring? *Crit Care Med* 1982: 10: 792-795.

[9] Shoemaker W. Monitoring and management of acute circulatory problems: The expanded role of the physiologically oriented critical care nurse. *Am J Crit Care* 1992: 1: 38-53.

[10] Card SK, Mackinlay JD, Schneiderman B. *Readings in Information Visualization: Using Vision to Think.* San Francisco: Morgan Kaufmann Publishers, Inc., 1999.

[11] Weinger M, Gurushanthaiah K. Graphical displays may allow more rapid and accurate detection of acute physiological changes. *Anesthes* 1994: 81, A579.

[12] Friesdorf W, Schwilk B, Hahanel J, Frett P. Ergonomics applied to an intensive care workplace. *Intens Care World* 1990: 7: 192-198.

[13] Cole WG, Stewart JG. Metaphor graphics to support integrated decision making with respiratory data. *Int J Clin Monit Comp* 1993: 10: 91-100.

[14] Hesselvik F, Carlsson C, Brodin B, Jorfeldt L, Schildt B. A hemodynamic profile diagram and its application in septic patients. *Acta Anaes Scand* 1985: 29: 706-711.

[15] Pinsky MR. Hemodynamic profile interpretation. In Tobin MJ, ed. *Principles and Practice of Intensive Care Monitoring.* NY: McGraw Hill, Health Professions Division, 1998; pp. 871-888.

[16] Vicente KJ, Rasmussen J. The ecology of human-machine systems II: Mediating "direct perception" in complex work domains. *Ecological Psychology* 1990: 2(3), 207-249.

[17] Vicente KJ. *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-based Work.* Mahwah, NJ: Erlbaum, 1999.

[18] Vicente KJ, Rasmussen J. Ecological interface design: Theoretical foundations. *IEEE Trans on Sys, Man, & Cyber* 1992: 22: 589-605.

[19] Gibson JJ. *The Senses Considered as Perceptual Systems*. Boston: Houghton-Mifflin, 1966

[20] Gibson JJ. *The Ecological Approach to Visual Perception.* Hillsdale, NJ: Erlbaum (1986, first published, 1979).

[21] Rasmussen J. *Information Processing and Human-machine Interaction: An Approach to Cognitive Engineering.* New York: North-Holland, 1986.

[22] Rasmussen, J. The role of hierarchical knowledge representation in decision making and system management. *IEEE Trans on Sys, Man, and Cybernet* 1985: SMC-15: 234-243.

[23] Pawlak WS, Vicente KJ. Inducing effective operator control through ecological interface design. *Int J Hum-Comp Studies* 1996: *44*: 653-688.

[24] Blike G. The emergent shape features in a gray-scale graphical display improve pattern recognition compared to an alphanumeric display. *Anesthes* 1997: 87: 394.

[25] Effken JA, Kim N-G, Shaw RE. Making the constraints visible: Testing the ecological approach to interface design. *Ergonom* 1997: 40: 1-27.

[26] Michels P, Gravenstein D, Westenskow DR. An integrated graphic data display improves detection and identification of critical events during anesthesia. *J Clin Monitor* 1997:13*:* 249-259.

[27] Tan JKH. *Health Management Information Systems: Theories, Methods, and Applications.* Gaithersburg, MD: Aspen, 1995.

[28] Hajdukiewicz JR, Doyle DJ, Milgram P, Vicente KJ, Burns CM. A work domain analysis of patient monitoring in the operating room. In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*. Santa Monica, CA: Human Factors Society, 1998; pp. 1038-1042.

[29] Bennett KB, Flach JM. Graphical displays: Implications for divided attention, focused attention, and problem solving. *Hum Fac* 1992: 34: 513-533.

[30] Rasmussen J. The human as a systems component. In Smith HT, Green TRG, eds. *Human Interaction with Computers*. London: Academic Press, 1980; pp. 67-96.

[31] Rasmussen J, Jensen A. Mental procedures in real-life tasks: A case study of electronic trouble shooting. *Ergonom* 1974: 17: 293-307.

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