Three Key Levers for Achieving Resilience in Medication Delivery with Information Technology

Emily S. Patterson, PhD,† David D. Woods, PhD,† Emilie M. Roth, PhD,‡ Richard I. Cook, MD,§ Robert L. Wears, MD, MS,|| and Marta L. Render, MD*¶*

Abstract: Over the past several years, there has been an increase in interest in translating human factors knowledge and methods, primarily used in complex, event-driven, sociotechnical settings such as aviation, to health care. In this article, we overview the primary concepts in cognitive systems engineering that may aid in formulating interventions in a variety of diverse medical settings to reduce the likelihood of patient harm. To improve resilience in medication delivery, we propose immediately incorporating 3 key levers: (1) scenario-based design and evaluation of interventions, (2) advanced information visualization techniques to reduce data overload in the electronic medical record, and (3) explicit consideration and documentation of asynchronous, interdisciplinary teamwork support during software requirements analysis, including a workload shifting analysis. For long-term progress, we recommend investing in research to better understand technical work in health care, specifically task requirements in work domains and the trade-offs and strategies that workers use to meet these demands.

Key Words: human factor, medication error, CPOE, bar coding, medical informatics

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OVERVIEW OF COGNITIVE SYSTEMS ENGINEERING

Over the past several years, there has been an increase in interest in translating human factors knowledge and methods, primarily developed and used in complex, event-driven, sociotechnical settings such as aviation, nuclear power, and the military, to improve care processes in a variety of health-care settings. In this article, we overview the primary concepts from one portion of the cognitive and human factors literature, cognitive systems engineering (CSE), which arguably has the greatest potential for contributing to the formulation of an effective agenda for reducing the likelihood of patient harm.

CSE is an interdisciplinary approach to the development of knowledge, principles, methods, tools, and techniques to guide the design of computerized systems intended to support human performance in complex settings with high consequences for failure.[1–6] In supporting human performance, we are concerned with cognitive functions such as problem solving, judgment, decision making, attention, perception, and memory. The basic unit of analysis and design in CSE is a cognitive system composed of human and machine agents in a work domain that is delineated by roles, work and communication norms, artifacts, and procedures. CSE draws primarily from the disciplines of cognitive psychology, cognitive science, computer science, human-computer interaction, and human factors.

In the past several years, there has been an increase in interest in translating CSE knowledge and methods to improve care processes in a variety of health-care settings. The CSE field was primarily established following repeated experiences with discontinuity between anticipated and actual effects on human performance with the introduction of new technologies. For instance, a set of aviation accidents followed, in conjunction with other events, automated switches in the flight mode made without the pilot's knowledge. In the 1992 accident, there were 87 fatalities out of 96 passengers and crew when an Airbus plane crashed into the Vosges mountains because while trying to program the angle of descent, ''−3.3", into the flight control unit, the crew did not notice that the aircraft's automation had switched to the HDG/V/S (heading/vertical speed) mode, creating a descent rate of 3300 ft/min instead of 800 ft/min.[7–9] For information technology in general, including the health-care sector, in a 1998 survey by the Standish Group, the success rate overall for completing software projects was found to be 26%. For 46%, the project was completed and operational but over budget, delayed, and delivered fewer features and functions than originally contracted. An example is the Denver baggage system, which after delaying the opening of the new Denver airport and being used for 10 years at an estimated cost of $600 million, was abandoned in favor of manual baggage handling. For 28%, the projects were canceled before completion. In addition, completion and implementation of software does not ensure effectiveness. In health care, a recent systematic review found that, of 97 randomized controlled trials, only 62 (64%) of computerized clinical decision support systems improved practitioner performance.[10]

From the *VA Getting at Patient Safety (GAPS) Center, Cincinnati, OH; †Institute for Ergonomics, The Ohio State University, Columbus, Ohio; ‡Roth Cognitive Engineering, Brookline, MA; §Cognitive Technologies Laboratory, University of Chicago, Chicago, Illinois; ||Health Center, University of Florida, Jacksonville, Florida; and ¶Department of Medicine, University of Cincinnati, Cincinnati, Ohio.

Correspondence: Emily Patterson, PhD, Ohio State University, 210 Baker Systems, 1971 Neil Ave, Columbus, OH 43210 (e-mail: patterson.150@osu.edu).

In seeking to create better predictive models of how technological and organizational change will impact human performance,[11] the types of questions that are often asked by cognitive systems engineers are:

- What factors contribute to task complexity?
- What range of tasks do domain practitioners perform?
- What strategies do expert and novice practitioners use to perform these tasks?
- What are the goals and constraints in the application domain?
- What are the gaps between implicit assumptions (embedded in software and policies and procedures) about how work is conducted and the actual technical work?
- How will technological or organizational change impact the ability of practitioners to achieve their goals under domain constraints?

What is a Cognitive System?

The basic unit of analysis and design in CSE is a cognitive system.[1] Woods and Roth[3] coined the term ''cognitive system triad'' to emphasize that 3 interconnected elements, which are shown in Figure 1, determine the quality of performance on a task: (1) the expertise and sources of error of *agents* who act on the world, (2) the challenges to be met in an *external world* or domain of interest, and (3) the *artifacts*, or tools, through which the agents experience and learn about the world.

Agents

Characteristics of agents are an important determinant of performance. A primary CSE strategy is to leverage knowledge of human information-processing characteristics, such as what is needed to attract attention to unexpected data, into principles and techniques for human-computer interface design. More specific examples are developing principles for graphical display design that capitalize on human perceptual characteristics,[12–14] developing models of human performance that enable explicit consideration of human memory and attention-processing constraints in system design,[15,16] and developing principles for the design of error-tolerant systems.[17–19]

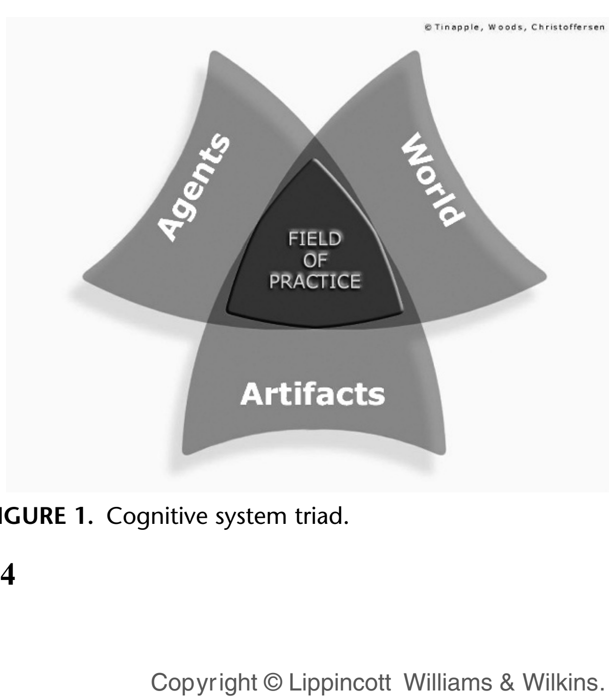

FIGURE 1. Cognitive system triad.

External World

Task requirements are domain-dependent and determine what is required for competent performance. Most important are factors that increase cognitive complexity because these largely determine the cognitive demands and range of situations agents will face:[20]

- how goals are achieved, including resolving conflicts between goals
- number and complexity of elements in a monitored process
- interactions and constraints that need to be considered in determining actions
- hazards to be avoided
- temporal characteristics or dynamics
- coupling between systems
- uncertainty
- risk

Artifacts

It is a fundamental finding in the cognitive psychological literature that how a problem is represented affects the cognitive work that is needed to solve the problem, referred to as the ''representation effect.''[21] For example, digital watches make it easy to determine the current time with a high degree of precision. Analog watches, although more difficult to read accurately, provide a better sense of duration (how long something takes). As a result, analog watches are more effective in teaching children the concept of time. In summary, the external representation of the domain embedded in supporting artifacts affects performance by making certain tasks easier at the expense of other tasks.

ARE ''ERRORS'' MADE BY COGNITIVE SYSTEMS?

Framing the base unit of analysis and design as a cognitive system composed of agents, the external world, and artifacts has nontrivial implications regarding the definition of errors, and therefore how to identify and prevent them.[22] One implication is that people and artifacts cannot be independently analyzed for contributions to a ''medication error.'' Therefore, it is not possible to choose between attributing error to a human as compared with a device or software program. For this reason, in addition to others, terms that specify how a medication delivery process failed to meet expectations, such as ''medication misadministration,'' are recommended instead of medication error. Note that this term also disambiguates the meaning of error, which confounds cause, failure, and process.[23]

The predominant view in health care is that *erratic people degrade an otherwise safe system*. The central focus of the approach derived from this view is preventing fundamentally error-prone individuals from making mistakes. Traditional attempts to reduce human error include encouraging the reporting of errors, developing taxonomies of error types to tabulate counts within the types, estimating likelihoods of error, and implementing procedures and technology to reduce error counts.

An alternative view is that *practitioners, supported by artifacts, are the primary source of resilience in creating safety in a domain* under resource and performance pressure. The approach derived from this view is the so-called new look and focuses on aiding people under pressure from conflicting goals to cope with complexity.[24–28] Attempts to improve patient safety are focused on increasing system resilience by investing in a context-sensitive understanding of the gaps that arise in system operation and the expert strategies that are used to bridge these gaps in practice.

THE NEW LOOK BEHIND HUMAN ERROR

This second approach, the so-called new look, is distinguished from the use of the label ''human error'' to attribute blame following an accident investigation. With the traditional approach, the frequent judgment that human error is a ''root cause'' of an incident generally serves as the stopping point for an investigation. As a result, recommendations to improve safety typically involve reminding people to be careful, educating them on the proper use of equipment, forcing them to comply more with procedures, and using automation to perform activities that used to be done by a human.

In contrast, when the label human error becomes the starting point for investigations, we find a deeper, multifaceted story.[29] This ''second story'' shows us how multiple interacting factors in complex systems can combine to produce systemic vulnerabilities to failure. For example, in an administration of an unintended chemotherapy agent,[30] we treated one physician's ''substitution error'' as the starting point for investigation. The deeper story included distractions due to driving while discussing the treatment plan; relying on the patient's memory for complex, technical information; trade-offs in initiating chemotherapy to address pressing clinical conditions when there were less experienced personnel and reduced staffing; coordination issues between radiotherapy and oncology experts; confusing, inconsistent protocols for accessing on-call resources on the weekend; inability to use computerized decision support for nonroutine requests; conversions between generic and brand medication names; multiple handoffs; and a degradation of inpatient chemotherapy expertise due to increased use of outpatient services. The second story is more complicated but more interesting and can point the way to learning and system improvements that can increase system resilience. The second story finds that doing things safely, in the course of meeting other goals, is and has always been part of operational practice. As people in their different roles are aware of potential paths to failure, they develop failure-sensitive strategies to forestall these possibilities.

Looking at technical work throughout an organization, we see people struggling to anticipate paths toward failure, actively adapting to create and sustain failure-sensitive strategies, and working to maintain margins in the face of pressures to do more and do it quickly. Failures occur against this background when multiple contributors—each necessary but only jointly sufficient—combine. Work processes do not choose failure but *drift toward it* as production pressures and change erode the defenses that normally keep failure at a distance. This drift is the result of systematic, predictable organizational factors at work, not simply erratic individuals.[31]

The following patterns are found in second stories:

- Workers continually revise their strategies to remain sensitive to the possibility for failure while adapting to increasing resource and production pressures.
- Workers are only partially aware of the potential for failure.
- Change creates new paths to failure and new demands; even strong and resilient coping strategies can become ineffective over time.
- Overconfidence in the coverage of anticipation of the types and mechanisms of failure.
- Missed side effects of change.

Very high levels of performance are achievable. For example, researchers have studied organizations that have been remarkably successful in managing potentially hazardous technical operations.[32] Achieving such high levels of performance does not flow from rooting out error, but rather through anticipating and planning for unexpected events and future surprises. Past success is not a reason for confidence; instead, continued investment in anticipating the changing potential for failure is energized by the deeply held understanding that our knowledge base is fragile in the face of the hazards inherent in work and the changes omnipresent in the environment.

In summary, analysis of second stories teaches us that failure represents *breakdowns in adaptations* directed at coping with complexity. Success is usually obtained as people learn and adapt to create safety in a world fraught with hazards, trade-offs, and multiple goals. In other words, success relates to organizations, groups, and individuals who produce resilient systems that adapt to change and surprise.

TOWARDS A MORE RESILIENT MEDICATION DELIVERY SYSTEM

From a CSE perspective, attempts to improve patient safety should primarily be focused on increasing system resilience to gaps in the continuity of care. Resilience is the broad application of failure-sensitive strategies that reduce the potential for and consequences from erroneous actions, surprising events, unanticipated variability, and complicating factors.[33] Several researchers have begun to explore how to increase system resilience to improve safety. A non-inclusive list is exploring barrier analysis,[34] looking at the resilience in surgical services,[35,36] analyzing an accident,[37] and characterizing how high-reliability organizations show high resilience.[38] Overall, the theme that leaps out from this work is that high-reliability organizations treat safety as a value, not a commodity. Rather than view past success as a reason to ramp down investments, these organizations continue to invest in anticipating the changing potential for failure because they appreciate that their knowledge of the gaps is imperfect and that their environment constantly changes.

A synthesis of the CSE literature suggests 5 promising strategies for improving patient safety in general (see Patterson et al,[22] in press, for an illustration of each strategy in the context of medication administration with Bar Code Medication Administration software used in all 163 Veteran's Health Administration hospitals):

1. *Model adaptive systems and variability:* Interventions to improve resilience need to be grounded in a detailed, context-sensitive understanding of how sharp end practitioners ''on the front lines'' adapt to cope with potential hazards in the face of variability and complexity.
2. *Identify unintended cascading effects from systemic change:* The introduction of any change, regardless how good, has unintended cascading effects that potentially create new paths to failure.[27] Proactively identifying these paths allows system redesign before undesired outcomes. There are several recent examples of this approach in health-care information technology.[39–41]
3. *Make activities and communications of team members observable:* A strategy for increasing system resilience from the Computer Supported Cooperative Work literature is ''listening in.'' For example, researchers observed that controllers thought out loud about schedule changes that they made during crisis situations in Line Control Rooms in the London Underground[42] When the controllers expressed changes out loud, others in the vicinity noted changes that affected their own schedules. They also had the opportunity to detect erroneous assessments or decisions before they were acted on. Similarly, Rochlin and colleagues noted for voice loop communications in aircraft carrier operations that ''everyone involved…is part of a constant loop of conversation and verification taking place over several different channels at once. At first little of this chatter seems coherent, let alone substantive, to the outside observer…one discovers that seasoned personnel do not 'listen' so much as monitor for deviations, reacting to almost anything that does not fit their expectations.''[43] Finally, paper flight strips that are used by air traffic controllers to track airplane movement have been attempted to be replaced by electronic versions. One reason for rejection of the electronic versions is that ''cocking'' of the paper flight strips can be seen by other controllers from a distance with little effort, and this was not possible with the electronic versions.[44]
4. *Encourage ''sacrifice decisions'':* One of the hallmarks of a highly resilient organization is that individuals feel encouraged to deviate from a planned path associated with high productivity to a path that ''sacrifices'' productivity to avoid a potential threat to safety, even when in hindsight there was no need to deviate. For example, in the recent Columbia space shuttle accident, engineers missed that foam hitting the wing can damage the integrity of the aircraft. The concern is not about whether foam hitting the wing had been investigated for its effects during landing. The concern is to model the ability to back off when practitioners feel like they are near a safety boundary and to monitor how well the organization has mapped and updated the safety boundaries. For example, in this case, NASA did not monitor the range of what had been tested to see if it needed to be broadened. It does not matter if organizational decision-makers are accurate in their sensitivity to risks in this framing—what matters is the degrees of freedom available to them to deviate from an expected path. Managers are often seen as meta-monitors who might override the astronauts, thereby reducing the ability. Or they might ask the astronaut if he is a ''go.'' Or there might be a policy that any team member can hold veto power on a go kind of decision. In signal detection theory, accuracy and decision criteria are 2 different parameters.[45] The pilot might be wrong or right, but if you *never* see anyone back off on a decision within an organization, that is evidence of a poor criterion setting.
5. *Monitor the gap between standard operating procedures and actual practice:* One frequently cited contributor to accidents is the failure to follow standard operating procedures. Nevertheless, this finding often glosses over the fact that the documented standard operating procedure and the actual practice often diverge. The standard operating procedure is a static image of work that is distanced from the event-driven, time-pressured local nature of continuously trading off priorities to meet sometimes-conflicting goals. Although there will always be a gap between documented standard operating procedures and actual practice, highly resilient systems continuously monitor and work to reduce the gap. The gap is reduced both by removing barriers to the intended method and by revising the description of the intended method as trade-offs are changed and to document exceptions. As the gap grows, predictions of how changes, such as new technologies, will impact work will be less grounded in an understanding of how work is accomplished. In addition, under production pressures, actual practices will drift toward increasing productivity at the cost of increasing risks of potentially catastrophic failures unless managers reinforce to practitioners the value of resisting this ''drift toward failure''[46] despite the lack of feedback that safety boundaries have eroded before failure.

KEY LEVERS FOR ACHIEVING RESILIENCE IN MEDICATION DELIVERY

For improving the robustness of the medication delivery processes, there are at least 3 key ''levers'' to pursue from a CSE perspective. These are:

1. *Scenario-based design and evaluation of interventions:* In a 1994 survey by the Standish Group, information technology executive managers cited user involvement as the primary reason that a project succeeds (16% of responses) and lack of user input (13% of responses) as the primary reason that a project fails (http://www.standishgroup.com/). An impressive set of sophisticated practice-centered techniques[47–52] has been developed to overcome predictable issues in user involvement in software design (in other words, it is not enough to simply have user representation in decision making about software features). Some common themes among these techniques is the use of *scenarios* that:
   - Are generated by independent groups without a vested interest and with a deep understanding of the domain challenges,

- Appropriately sample the ''problem solving'' space for multiple user types,
- Include challenging and nominal (idealized) scenarios,
- Identify ''boundary conditions'' for when the tool can adequately support users,
- Elicit feedback on usefulness of the support concept embedded in the tool and on usability of the interface,
- Support envisioning of how the tool will transform the nature of practice in advance of implementation.

2. *Advanced information visualization techniques to reduce data overload in the electronic medical record:* As health care continues to transform from primarily paper-based records to electronic records, it should become increasingly clear that enabling electronic access to data is insufficient to aid human performance because of the so-called data overload problem.[53–55] Advanced information visualization techniques,[56] increasingly referred to as *Visual Analytics*, show potential for helping users to avoid missing critical data that are available in principle but not easy to detect in actuality because of the inability to ''look at it all.'' Although the approaches are varied, a common theme is overcoming the so-called keyhole effect[14] from the relatively small amount of ''screen real estate'' on computer screens (as compared with paper) through the use of overview, integrated displays[57] that graphically depict data relationships to aid detection of events and other patterns.
3. *Explicit consideration and documentation of asynchronous, interdisciplinary teamwork support during software requirements analysis, including a workload shifting analysis:* Failures to adopt technology attributed to workload shifting issues have occurred so frequently that Norman termed the finding[58] as ''Grudin's Law'': ''When those who benefit are not those who do the work, then the technology is likely to fail or, at least, be subverted.''[59] An important objective for U.S. healthcare systems in the next decade is to improve interdisciplinary teamwork in a patient-centered fashion. Explicit consideration of how to support asynchronous coordination across multiple user groups during requirements analysis may enable step change improvements on this objective. In principle, in a patient-centered system, there will be no information technology that will support a single user group. For example, computerized order entry systems need to be designed with explicit consideration for the needs of pharmacists and nurses, even if physicians are the only users ordering medications. As has been recently noted,[60] an important caveat is that changes in work roles and processes should not be ''pushed'' through software design. As part of an explicit consideration of how to support teamwork, a workload shifting analysis is a tool that may help avoid predictable implementation failures.

SUMMARY

Despite the increase in interest in translating human factors knowledge and methods to health care, it has proven difficult for human factors experts to significantly contribute to the formulation of an effective national agenda for decreasing patient harm. Although this minimal impact can partially be attributed to the predictable misunderstandings and differences in core values that occur when cultures clash for the first time, there also seems to be a fundamental difference of opinion over the nature of human error. In particular, when the base unit of analysis and design is a cognitive system, the notion of errors, including how to identify and prevent errors, is profoundly altered. Strategies to address the ''human error problem'' as traditionally defined have the potential to lead to unintended consequences, including rushing the installation of clinical healthcare information technology to forestall error by practitioners and failing to learn about how software programs can contribute to undesired outcomes. As Richard Cook has noted (listserv posting RISKS 23.81 in response to Koppel, 2005): ''It is unsettling and disappointing to realize that the efforts to produce really good information technology are going to require a great deal more time, effort, and money than has been budgeted. Many hospitals are already deeply involved in buying and installing new information technology and government pressure to continue this effort is likely to continue.''

From a CSE perspective, what is most needed is a detailed, calibrated understanding of the actual task requirements of the work domain and the trade-offs and strategies that workers use to meet these demands. Ideally, a parallel and equally funded research effort to understand the technical work of health care will be undertaken along with implementation efforts so that, in time, it will be possible to make better, more useful, and more practice-centered technology.

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REFERENCES

1. Roth EM, Patterson ES, Mumaw RJ. Cognitive engineering: issues in user-centered system design. In: Marciniak J, ed. *Encyclopedia of Software Engineering*, 2nd ed. New York: Wiley-Interscience, John Wiley and Sons; 2001.
2. Norman DA. Steps toward a cognitive engineering. *Program in Cognitive Science*. University of California at San Diego; 1981. Technical Report.
3. Woods DD, Roth EM. Cognitive engineering: human problem solving with tools. *Hum Factors*. 1988;30:415–430.
4. Hollnagel E. Comments on 'Conception of the cognitive engineering design problem' by John Dowell and John Long. *Ergonomics*. 1998;41(2):160–162.
5. Woods DD, Hollnagel E. *Joint Cognitive Systems: Patterns in Cognitive Systems Engineering*. Boca Raton, FL: Taylor & Francis. In press.
6. Hollnagel E, Woods DD. *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*. Boca Raton, FL: Taylor & Francis; 2005.
7. Lenorovitz JM. French Government Seeks A320 Changes Following Air Inter Crash Report. *Aviation Week and Space Technology*. March 2, 1992:30–31.

8. Sarter NB, Woods DD, Billings CE. Automation surprises. In: Salvendy G, ed. *Handbook of Human Factors and Ergonomics*, 2nd ed. New York, NY: Wiley; 1997:1926–1943.
9. Sarter NB, Woods DD. Teamplay with a powerful and independent agent: a full-mission simulation study. *Hum Factors*. 2000;42(3):390–402.
10. Garg AX, Adhikari NKJ, McDonald H, et al. Effects of computerized clinical decision support systems on practitioner performance and patient outcomes: a systematic review. *JAMA*. 2005;293(10): 1223–1228.
11. Woods DD, Dekker S. Anticipating the effects of technological change: a new era of dynamics for human factors. *Theor Issues Ergon Science*. 2000;1(3):1–11.
12. Cleveland WS. *The Elements of Graphing Data*. Monterey, CA: Wadsworth Advanced Book Program; 1985.
13. Sanderson PM, Haskell I, Flach J. The complex role of perceptual organization in visual display design theory. *Ergonomics*. 1992;35:1199–1210.
14. Woods DD. Visual momentum: a concept to improve the cognitive coupling of person and computer. *Int J Man-Mach Stud*. 1984;21:229–244.
15. Card SK, Moran T, Newell A. *The psychology of human-computer interaction*. Hillsdale, NJ: Lawrence Erlbaum and Associates; 1983.
16. Kieras DE, Polson PG. An approach to the formal analysis of user complexity. *Int J Man-Mach Stud*. 1985;22:365–94.
17. Brown JS, Newman S. Issues in cognitive and social ergonomics: from our house to Bauhaus. *Hum-Comput Interact*. 1985;1:359–91.
18. Norman DA. Design rules based on analyses of human error. *Commun ACM*. 1983;26:254–258.
19. Woods DD, Johannesen L, Cook RI, et al. *Behind Human Error: Cognitive Systems, Computers and Hindsight*. Dayton, OH: Crew Systems Ergonomic Information and Analysis Center, WPAFB; 1994.
20. Woods DD. Coping with complexity: the psychology of human behavior in complex systems. In: Goodstein LP, Andersen HB, Olsen SE, eds. *Mental Models, Tasks and Errors*. London: Taylor and Francis; 1988:128–148.
21. Zhang J, Norman DA. Representations in distributed cognitive tasks. *Cogn Sci*. 1994;18:87–122.
22. Patterson ES, Cook RI, Woods DD, et al. Gaps and resilience. In: Bogner MS, ed. *Human Error in Medicine*, 2nd ed. Hillsdale, NJ: Erlbaum. In press.
23. Woods DD, Cook RI. Mistaking error. In: Youngberg BJ, Hatlie M, eds. *The Patient Safety Handbook*. Sudbury, MA: Jones and Bartlett; 2004.
24. Rasmussen J. *Information Processing and Human-Machine Interaction*. New York: North Holland; 1986.
25. Rasmussen J. The role of error in organizing behavior. *Ergonomics*. 1990;33:1185–1199.
26. Rasmussen J. Human error and the problem of causality in analysis of accidents. *Philos Trans R Soc Lond B*. 1990;327:449–462.
27. Rasmussen J. Risk management, adaptation, and design for safety. In: Brehmer B, Sahlin NE, eds. *Future Risks and Risk Management*. Dordrecht: Kluwer Academic; 1994.
28. Rasmussen J. The concept of human error: is it useful for the design of safe systems in health care? In: Vincent C, deMoll B, eds. *Risk and Safety in Medicine*. London: Elsevier; 1999.
29. Cook RI, Woods DD, Miller C. A Tale of Two Stories: Contrasting Views on Patient Safety. National Patient Safety Foundation, Chicago IL, April 1998. Available at: www.npsf.org/exec/report.html.
30. Patterson ES, Cook RI, Woods DD, et al. Examining the complexity behind a medication error: generic patterns in communication. *IEEE Trans Syst Man Cybern A Syst Humans*. 2004;34(6):749–756.
31. Woods DD. Creating Foresight: How Resilience Engineering Can Transform NASA's Approach to Risky Decision Making. Testimony on *The Future of NASA* to Senate Committee on Commerce, Science and Transportation, John McCain, Chair, Washington D.C., October 29, 2003.
32. Rochlin GI. Safe operation as a social construct. *Ergonomics*. 1999;42(11):1549–1560.
33. Hollnagel E, Woods DD, Leveson N, eds. *Resilience Engineering*. Aldershot, UK: Ashgate. In press.
34. Svenson O. Accident and incident analysis based on the accident evolution and barrier function model. *Cognition, Technology, and Work*. 2001;3:42–52.
35. Carthey J, deLeval MR, Reason JT. Human factor in cardiac surgery: errors and near misses in a high technology medical domain. *Ann Thorac Surg*. 2001;72(1):300–305.
36. Uhlig PN, Brown J, Nason AK, et al. System innovation: Concord Hospital. *Jt Comm J Qual Improv*. 2002;28(12):666–672.
37. Woods DD, Shattuck LG. Distant supervision—local action given the potential for surprise cognition. *Technology and Work*. 2000;2:86–96.
38. Weick KE, Sutcliffe KM, Obstfeld D. Organizing for high reliability: processes of collective mindfulness. *Res Organ Behav*. 1999;21:81–123.
39. Koppel R, Metlay JP, Cohen A, et al. Role of computerized physician order entry systems in facilitating medication errors. *JAMA*. 2005;293(10):1197–1203.
40. Embi PJ, Yackel TY, Logan J, et al. Impacts of computerized physician documentation in a teaching hospital: perceptions of faculty and resident physicians. *J Am Med Inform Assoc*. July–August 2004;11(4):300–309.
41. Patterson ES, Cook RI, Render ML. Improving patient safety by identifying side effects from introducing bar coding in medication administration. *J Am Med Inform Assoc*. 2002;9(5):540–553.
42. Luff P, Heath C, Greatbatch D. Tasks-in-interaction: paper and screen based documentation in collaborative activity. *CSCW '92 Proceedings*. 1992:163–170.
43. Rochlin GI, La Porte TR, Roberts KH. The self-designing high-reliability organization, aircraft carrier flight operations at sea. *Naval War Coll Rev*. 1987:76–90.
44. Mackay WE. Is paper safer? The role of paper flight strips in air traffic control. *ACM Trans Comp-Human Interact*. 2000;6(4):311–40.
45. Green DM, Swets JA. *Signal Detection Theory and Psychophysics*. New York: Wiley; 1966.
46. Reason J. *Managing the Risks of Organizational Accidents*. Brookfield, VT: Ashgate; 1997.
47. Carroll JM, ed. *Scenario-based design: envisioning work and technology in system development*. New York: John Wiley & Sons; 1995.
48. Roth EM, Woods DD. Aiding human performance I: from cognitive analysis to support systems. *Le Travail Humain*. 1988;51(1):39–64.
49. Roth EM, Woods DD. Cognitive task analysis: an approach to knowledge acquisition for intelligent system design. In: Guida G, Tasso C, eds. *Topics in Expert System Design*. New York: Elsevier Science Publishers BV (North-Holland); 1990:233–264.
50. Potter SS, Roth EM, Woods DD, et al. Bootstrapping multiple converging cognitive task analysis techniques for system design. In: Schraagen JMC, Chipman SF, Shalin VL, eds. *Cognitive Task Analysis*. Mahwah, NJ: Lawrence Erlbaum Associates; 2000:317–340.
51. Sanders EBN. Generative tools for co-designing. In: Scrivener S, Ball LJ, Woodcock A, eds. *Collaborative Design*. London: Springer-Verlag; 2000:3–12.
52. Dekker S, Woods DD. Extracting data from the future: assessment and certification of envisioned systems. In: Dekker S, Hollnagel E, eds. *Coping with Computers in the Cockpit*. Ashgate: 1999:7–27.
53. Miller JG. Information input overload and psychopathology. *Am J Psychiatr*. 1960;116:695–704.
54. Woods DD, Patterson ES, Roth EM. Can we ever escape from data overload? A cognitive systems diagnosis. *Cognition, Technology, and Work*. 2002;4(1):22–36.
55. Patterson ES, Roth EM, Woods DD. Predicting vulnerabilities in computer-supported inferential analysis under data overload. *Cognition, Technology, and Work*. 2001;3(4):224–237.
56. Card SK, Mackinlay JD, Schneiderman B. *Readings in information visualization: using vision to think*. San Francisco, CA: Morgan Kaufmann Publishers; 1999.
57. Vicente KJ. Ecological interface design: progress and challenges. *Hum Factors*. 2002;44:62–78.
58. Grudin J. Computer-supported cooperative work: history and focus. *IEEE Computer*. 1994;27(5):19–27.
59. Norman DA. *Things that make us smart—defending human attributes in the age of the machine*. Reading, MA: Addison-Wesley; 1993:113.
60. Wears RL, Berg M. Computer technology and clinical work: still waiting for Godot. *JAMA*. 2005;293(10):1261–1263.