29

BEHIND HUMAN ERROR: TAMING COMPLEXITY TO IMPROVE PATIENT SAFETY

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Throughout the patient safety movement, health care leaders have consistently referred to the potential value of human factors research on human performance and system failure (Leape, 2004; Leape, Woods, Hatlie, Kizer, Schroeder, & Lundberg 1998). The patient safety movement has been based on three ideas derived from results of research on human expertise (Feltovich, Ford, & Hoffman, 1997), collaborative work (Rasmussen, Brehmer, & Lepat, 1991), and high-reliability organizations (Rochlin, 1999) built up through investments by other industries:

- Adopt a systems approach to understand how breakdowns can occur and how to support decisions in the increasingly complex worlds of health care,
- Move beyond a culture of blame to create open flow of information and learning about vulnerabilities to failure, and
- Build partnerships across all stakeholders in health care to set aside differences and to make progress on a common overarching goal.

Implementing these ideas requires detailed study, careful assessment, and thoughtful application of approaches that are unfamiliar to health care workers and managers. Success depends on creating durable, informative, and useful partnerships between health care and disciplines with core expertise in areas of human performance. Sustained, substantive partnerships are needed to devise useful approaches to current problems and to anticipate and block the new paths to failure that accompany changes in health care. (Woods & Cook, 2001).

PARALLEL PERSPECTIVES

> Human error in medicine, and the adverse events which may follow, are problems of psychology and engineering not of medicine.—Senders, 1993

Health care organizations and the public demand that we reduce injuries to patients during treatment. From one perspective, medication misadministrations, delayed diagnoses, or wrong site surgeries are events that arise from specific medical issues. From another perspective, these adverse events evolve because of the lawful, predictable effects of factors that affect human performance. Decision making, attentional processes, the use of knowledge, and coping with uncertainty are not medical issues but human performance issues that play out in a health care context.

The research base about human performance was built by studying how practitioners handle routine and challenging situations in aviation, industrial process control, military command and control, and space operations. The studies demonstrate empirical regularities and provide explanatory concepts and models of human performance. These results allow us to see common underlying patterns behind the superficial variability that makes different settings appear unique.

Understanding, predicting, and modulating human performance in any complex setting requires a detailed understanding of both the setting and the factors that influence performance. There are different languages used to describe human performance. These basic themes are the platform—the anatomy and physiology—of human performance in real-world settings. To understand patterns in human *judgment,* one needs to understand concepts such as bounded rationality, knowledge calibration, heuristics, and oversimplification fallacies (Feltovich et al., 1997). To understand patterns in *communication and cooperative work,* one needs to understand concepts such as supervisory control, common ground, communication of intent, and open versus closed work spaces (Clark & Brennan, 1991; Galegher, Kraut, & Egido, 1990; Greenbaum & Kyng, 1991; Rasmussen et al., 1991; Woods & Shattuck, 2000). To understand patterns in *human–computer cooperation,* one needs to understand concepts such as the representation effect, object displays, inattentional blindness, mental models, data overload, and mode error (LaBerge, 1995; Norman, 1993; Rensink, O'Regan, & Clark, 1997; Vicente, 1999; Zhang, 1997).

The complexity and connected nature of health care work ensures that many human performance themes will be found when examining a particular problem and that a single pattern will play out in many different health care settings. Consider the following two medication misadministrations, both of which could be classified as "wrong dose" medication errors. In the first case, an infusion pump was thought to be off when it was actually infusing medication in an unconstrained fashion. In the second case, a patient received two doses of an ordered medication: one from a nurse responding to a verbal order and one from a different nurse on the next shift administering the same medication from the order later entered by the physician into the computerized physician order-entry system. Both of these cases involve some of the same themes, such as poor coordination between multiple providers caring for the same patient, poor observability of the history of recent medication administrations, high workload, and overreliance on memory by frequently interrupted providers. Yet interventions stemming from these cases could be quite different: In the first case, potential interventions could be new software reliability checks, new pattern-based visualizations, automated free-flow protection in infusion devices, and in the second case, the system could highlight potential duplicate orders or enable documentation of administration by a nurse prior to order entry by a physician. This many-to-many mapping of themes in human performance to specific health care topics is one reason that work on patient safety remains difficult: Rather than requiring a particular type of human factors knowledge for progress, these complex problems usually involve the entire range of expertise on human performance. Similarly, it explains some of the challenges in using classifications such as "wrong dose medication error" to prioritize interventions because the classifications are based on failure modes rather than underlying patterns of systemic factors.

To use the human factors knowledge base to support very high levels of human performance in a particular health care setting requires a detailed understanding not only of how these themes play out in the health care setting but also of the technical details that determine medical success and failure. Put another way, to deal effectively with specific problems in health care requires an understanding of both the human performance factors and the medical domain knowledge. Gaining this understanding requires going back and forth between two different perspectives. This is only possible in a genuine collaboration where each party deliberately steps outside of his or her own area of expertise in order to learn from the other's perspective.

Patient safety research requires interdisciplinary synthesis that combines technical knowledge in specific health care areas with technical knowledge of human performance issues that play out in that area as practitioners perform this kind of work in context. Indeed, partnerships of this kind have been and continue to be the engine of progress in work on patient safety to date (see Bogner, 1994), for example, programs such as the Annenberg meetings (see Hendee, 1999) and partnerships at various research labs around the United States and the world.

STARTLING RESULTS FROM THE SCIENCE

One of the great values of science is that, during the process of discovery, conventional beliefs are questioned by putting them in empirical jeopardy. When scientists formulate new ideas and look at the world anew through these conceptual looking glasses, the results often startle us. As a result, we can innovate new approaches to accomplish our goals.

This process has been going on for more than 20 years in the "new look" at the factors behind the label human error (Reason, 1997; Rasmussen, 1990a, 1990b, 2000; Woods, Johannesen, Cook, & Sarter, 1994). Driven by surprising failures in different industries, researchers from different disciplinary backgrounds began to reexamine how systems failed and how people in their various roles contributed to both success and failure. The results often deviated from conventional assumptions in startling ways.

The research found that doing things safely, in the course of meeting other goals, is always 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. When failures occurred against this background of usual success, researchers found multiple contributors, each necessary but only jointly sufficient, and a process of drift toward failure as planned defenses eroded in the face of production pressures and change. The research revealed systematic, predictable organizational factors at work, not simply erratic individuals. The research also showed that to understand episodes of failure, one had to first understand usual success—how people in their various roles learn and adapt to create safety in a world fraught with hazards, trade-offs, and multiple goals (Cook, Render, & Woods, 2000; Hollnagel, 2004).

Researchers have studied organizations that manage potentially hazardous technical operations remarkably successfully, and the empirical results have been quite surprising also (Rochlin, 1999). Success was not related to how these organizations avoided risks, reduced errors, or prioritized interventions based on probabilities of failure, but rather how these high-reliability organizations created safety by anticipating and planning for unexpected events and future surprises. These organizations did not take past success as an excuse for confidence. Instead they continued to invest in anticipating the changing potential for failure because of the deeply held understanding that their knowledge base was fragile in the face of the hazards inherent in their work and the changes omnipresent in their environment. Safety for these organizations was not a commodity but a value that required continuing reinforcement and investment. The learning activities at the heart of this process depended on open flow of information about the changing face of the potential for failure. High-reliability organizations valued such information flow, used multiple methods to generate this information, and then used this information to guide constructive changes without waiting for accidents to occur.

Perhaps most startling in this research is the finding that the source of failure was not those who are less careful or motivated than those that are more careful or motivated. Instead, the process of investing in safety begins with each person being willing to question his or her beliefs to learn surprising things about how *he or she* can contribute to the potential for failure in a changing and limited resource world.

'EMS ISSUES FOR RESEARCH TO IMPROVE SAFETY

Search for Ur lerl ıg Patterr Gain Leverag

From past work, progress has come from going beyond the surface descriptions (the phenotypes of failures) to discover underlying patterns of systemic factors (generic or genotypical patterns). These patterns capture repeated results about how people, teams, and organizations coordinate activities, information, and problem solving to cope with the complexities of problems that arise (Hollnagel, 1993).

The surface characteristics of a near-miss or adverse event are unique to a particular setting and people. Generic patterns reappear in many specific situations. Research in human factors has revealed a wealth of patterns, for example,

- Garden path problems and the potential to fixate on one point of view or hypothesis in problem solving (De Keyser & Woods, 1990; Patterson, Cook, Woods, & Render, 2004; Nguyen, Halloran, & Asch, 2004).
- Missing side effects of an action or change to a plan in highly coupled systems (Rasmussen, 1986).
- Hindsight bias from knowledge of outcome (Fischhoff, 1975).
- Local actors having difficulty tailoring a plan when the situation changes without an understanding of the intent behind an order (Woods & Shattuck, 2000).

- Alarm overload and high false alarm rates leading to missed or ignored warnings (Stanton, 1994).
- Mode errors in computerized devices with multiple modes and poor feedback about device state (Norman, 1988).

A great deal of leverage for improvements is gained by identifying the generic patterns at work in a particular situation of interest (Woods, 2005). For example, we can sample the kinds of difficult situations that can occur in a health care setting and recognize the presence of garden path problems (e.g., in anesthetic management; Gaba, Maxwell & DeAnda, 1987). We may review a corpus of near-misses and note that in several cases a practitioner became fixated on one view of the situation (Cook, McDonald, & Smalhout, 1989). Or we may analyze how people handle simulated problems and see the potential for fixating in certain situations (e.g., as has occurred in crisis training via anesthesia simulators; Howard, Gaba, Fish, Yang, & Sarnquist, 1992; Rudolph, 2003).

Previous work on aiding human and team situation assessment can now seed and guide the development of interventions. To overcome fixation in a garden path problem, one can bring to bear techniques that may break up frozen mindsets such as new kinds of pattern-based displays or new team structures that help broaden the issues under consideration (De Keyser & Woods, 1990; Patterson, Cook, et al., 2004).

Each of the genotypes listed earlier was identified and studied in aerospace, process control, or military settings, but they all also play out in multiple health care settings:

- Fixation as a danger in anesthetic management during surgery (Cook et al., 1989; Rudolph, 2003).
- Missing side effects of planned changes that create new complexities or vulnerabilities (Embi et al., 2004; Patterson, Cook, & Render, 2002).
- Missed warnings or reminders due to high nuisance and false alarm rates in intensive care units (Patterson, Doebbling, et al. 2005; Weinger & Smith, 1993; Xiao, Seagull, Nieves-Khouw, Barzac, & Perkins, 2004).
- Mode errors in computerized infusion devices (Cook, Woods, & Howie, 1992; Cook, Woods, & Miller, 1998; Lin et al., 1998; Nunnally & Cook, 2004).
- Hindsight bias in incident review teams (Caplan, Posner, & Cheney, 1991).

This list is very short and only exemplifies some of the results available to jump-start research and design in health care settings (e.g., for other generic patterns linked to the Columbia accident that also appear in health care organizations, see Woods, 2005b).

Research on patient safety should be using and expanding the set of generic patterns related to breakdowns in human performance that occur in health care settings. Research should focus on developing and testing interventions to reduce these problems. In many cases, previous work has identified the interventions needed (e.g., in the case of mode errors). In other cases, seed ideas exist that need to be further developed given the unique pressures of health care.

Tame Complexity

In the final analysis, the enemy of safety is complexity. In nuclear power and aviation, we have learned at great cost that often it is the underlying complexity of operations that contributes to human performance problems. Simplifying the operation of the system can do wonders to improve its reliability, by making it possible for the humans in the system to operate effectively and more easily detect breakdowns. Often, we have found that proposals to improve systems founder when they increase the complexity of practice (e.g., Xiao et al., 1996). Adding new complexity to already complex systems rarely helps and can often make things worse. This applies to system improvements justified on safety grounds as well.

The search for operational simplicity has a severe catch however. The very nature of improvements and efficiency in health care delivery includes, creates, or exacerbates many forms of complexity. Ultimately, success and progress occur through monitoring, managing, taming, and coping with the changing forms of complexity, and not by mandating simple, one-size-fits-all policies.

This has proven true particularly with respect to efforts to introduce new forms and levels of computerization. Improper computerization can simply exacerbate or create new forms of complexity to plague operations (Woods et al., 1994). The situation is complicated by the fact that new technology often has benefits at the same time that it creates new vulnerabilities.

Again the science startles us. To help people in their various roles create safety, research needs to (Cook et al., 2000; Woods & Cook, 2002):

> Search out the sources of complexity, including the "edges" where simple approaches fail.
>
> Understand the strategies people, teams, and organizations use to cope with complexity.
>
> Devise better ways to help people cope with complexity to achieve success.

Adding to a system's or organization's resilience is one of the basic lessons for taming complexity (Carthey, de Leval, & Reason, 2000; Sutcliffe & Vogus, 2003; Woods, 2005b; Hollnagel, Woods & Leveson, 2006).

Adopt Methods for User-Centered Design of Information Technology

When human factors practitioners and researchers examine the typical human interface of computer information systems and computerized devices in health care, they are often shocked. What we take for granted as the least common denominator in user-centered design and testing of computer systems in other high-risk industries (and even in commercial software development houses that produce desktop educational and games software) seems to be far too rare in medical devices and computer systems. The devices are too complex and require too much training to use, given typical workload pressures (e.g., Cook et al., 1992; Nunnally & Cook, 2004; Obradovich & Woods, 1996; Rogers, Mykityshyn, Campbell, & Fisk, 2001).

Computer displays, interfaces, and devices in health care exhibit "classic" human–computer interaction deficiencies. By "classic" we mean that we see these design "errors" in many devices in many settings of use, that these design problems are well understood (i.e., they appear in our textbooks and popular writings; e.g., Norman, 1988; Norman & Draper, 1986), and that the means to avoid these problems are readily available.

We are concerned that the calls for more use of integrated computerized information systems to reduce error could introduce new and predictable forms of error unless there is a significant investment in user-centered design (Winograd & Woods, 1997).

The concepts and methods for user-centered design are available and are being used every day in software houses (Carroll & Rosson, 1992; Flach & Dominguez, 1995; Nielsen, 1993). Focus groups, cognitive walkthroughs, and interviews are conducted to generate a cognitive task analysis that details the nature of work to be supported by a product (Chung, Zhang, Johnson, & Patel, 2003; Garmer, Liljegren, Osvalder, & Dahlman, 2000; Lin, Vicente, & Doyle, 2001; Zhang, Johnson, Patel, Paige, & Kubose, 2003). Iterative usability testing of a system prior to use with a handful of representative users has become a standard, not an exceptional, part of most product development practices. "Out of the box" testing is conducted to elicit feedback on how to improve the initial installation and use of a fielded product. Health care delivery organizations also need to understand how they can use these techniques in their own testing processes and as informed consumers of computer information systems.

Building partnerships, creating demonstration projects, and disseminating the techniques for health care organizations is a significant and rewarding investment to ensure that the health care industry receives the benefits of computer technology while avoiding designs that induce new errors (Kling, 1996).

But there is much more to human–computer interaction than adopting basic techniques such as usability testing (Karsh, 2004). Much of the work in human factors research concerns how to use the potential of computers to enhance expertise and performance. We consider only a few of these issues here.

Study Human Expertise to Develop the Basis for Computerization

The key to skillful rather than clumsy use of technological possibilities lies in understanding both the factors that lead to expert performance and the factors that challenge expert performance (Feltovich, Ford, & Hoffman, 1997). Once one understands the factors that contribute to expertise and to breakdown, one then will understand how to use the powers of the computer to enhance expertise. This is an example of a more general rule—to understand failure and success, first begin by understanding what makes some problems difficult.

The areas of research on human performance in medicine explored in the monograph *A Tale of Two*

Stories (Cook, Woods, & Miller, 1998) illustrate this process. In these cases, progress depended on investigations that identified the factors that made certain situations more difficult to handle and then explored the individual and team strategies used to handle these situations. As the researchers began to understand what made certain kinds of problems difficult, how expert strategies were tailored to these demands, and how other strategies were poor or brittle, new concepts were identified to support and broaden the application of successful strategies. In each of these cases, the introduction of new technology helped create new dilemmas and difficult judgments. In addition, once the basis for human expertise and the threats to that expertise had been studied, new technology was an important means to achieve enhanced performance.

We can achieve substantial gains by understanding the factors that lead to expert performance and the factors that challenge expert performance. This provides the basis to change the system, for example, through new computer support systems and other ways to enhance expertise in practice (Nyssen & De Keyser, 1998).

Make Machine Advisors and Automation Team Players

New levels of automation have had many effects in operational settings. There have been positive effects from both economic and safety points of view. Unfortunately, operational experience, research investigations, incidents, and occasionally accidents have shown that new and surprising problems have arisen as well. Computer agents can be brittle and only able to handle a portion of the situations that could arise. Breakdowns in the interaction between operators and computer-based automated systems can also contribute to near-misses and failures in these complex work environments (Guerlain et al., 1996).

Over the years, human factors investigators have studied many of the "natural experiments" in human–automation cooperation—observing the consequences in cases where an organization or industry shifted levels and kinds of automation. One notable example has been the many studies of the surprising consequences of new levels and types of automation on the flight deck in commercial transport aircraft (Billings, 1996).

The overarching result from the research is that for automation concerned with information processing and decision making to be successful, the key requirement is to design for fluent, coordinated interaction between the human and machine elements of the system. In other words, automated and intelligent systems must be designed to be "team players" (Malin et al., 1991; Roth, Malin, & Schreckenghost, 1997). When automated systems increase autonomy or authority of machines without new tools to support cooperation with people, we find automation surprises contributing to incidents and accidents (Sarter, Woods, & Billings, 1997).

Human factors research has abstracted many patterns and lessons about how to make automated systems team players (Christoffersen & Woods, 2002). Characteristics of successful automation generally include predictability of what the automation will do, inspectability of the basis for action by the automation, high reliability in the most frequent operational situations, observability of the situations in which the automation will fail, direct benefit to the users that are greater than the costs of inputting information for automated processing, and the ability to switch to less automated modes on demand (Klein, Woods, Bradshaw, Hoffman, & Feltovich, 2004; Norman, 1990). One concern with using automated systems is that people have been shown to be more willing to accept even *poor* advice when it comes from a computer and have difficulty revising machine-initiated solutions (e.g., Layton, Smith, & McCoy, 1994). Therefore a useful tactic is to have humans initiate a problem-solving sequence and then use automated systems to remind, suggest, critique, or broaden the factors considered by the human decision maker, even for cases where the computer is unable to generate a good solution on its own (Guerlain et al., 1999).

Many of the developments in computer information systems across health care delivery systems (be they intended to enhance safety or productivity) include embedded forms of automation. Using the lessons from past research to guide the design of automated information processing systems will help avoid new paths to failure and increase the benefits to be obtained from these investments in new technology.

Invest in Collaborative Technologies

> When I order a medication, I think the patient gets the medication directly, but there are many other steps, computer systems, and

hands that intervene in the process. -A physician, 2000

Health care, similar to other settings, is increasingly shifting from paper-based to computer-based systems (Ash, Berg, & Coiera 2004). In the transition, the fundamental distribution of patient care over multiple practitioners, groups, locations, and organizations is easily overlooked or oversimplified by design teams. Collaborative support in prior systems can therefore be unintentionally degraded in new systems, as was experienced with a bar code medication system that initially did not support easy physician access to the complete medication administration record (Patterson et al., 2002).

In addition, opportunities have increased to provide more remote and distributed care through telemedicine (LaMonte et al., 2000; Xiao, Mackenzie, Orasanu, & the LOTAS Group, 1999), web-based consults, and remote surgeries via robotic technology. This change challenges us to coordinate care over these disparate players. We often think that if these different players are connected through new information technology, effective coordination will follow automatically. The exploding field of computer supported cooperative work (CSCW) tells us that achieving high levels of coordination is a special form of expertise requiring significant investment in experience or practice (Clark & Brennan, 1991; Galegher et al., 1990; Greenbaum & Kyng, 1991; Grudin, 1994; Klein et al., 2005). It also tells us that making cooperative work through a computer effective is a difficult challenge. For example, a critical part of effective collaboration is how it helps broaden deliberations and cross-check judgments and actions to detect and recover from incipient failures (Patterson, Cook, et al., 2004). The design of the communication channel and information exchanged can degrade the cross-check function or enhance it, depending on how the channel is designed. A great deal of work is underway to try to identify what factors are important to support good collaborative work to guide investments in technology (e.g., Guerlain et al., 2001; Heath & Luff, 1992; Jones, 1995; Moss & Xiao, 2004; Nyssen & Javaux, 1996; Patterson, Roth, et al., 2004; Xiao et al., 1999).

The field of CSCW is exploding because of the advances in the technology of connectivity—the Internet and telecommunications in general—and because of the potential benefits of being connected. This leads designers to need information about the basis for high levels of skill at coordinated work.

The new technologies of connectivity will transform the face of health care practices, and CSCW should become a core area of expertise, research, and development in health care. Relationships between practitioners will change and new relationships will be introduced. The changes can be designed primarily to support efficiency, or they can be designed primarily to enhance safety. Side effects of these coming changes can also create new paths to failure while they block other paths. Research to understand and direct this wave of change to enhance safety will need to be a critical priority in health care as it is in other high-performance fields.

The development and impact of telemedicine is one example of this process. Achieving continuity of care in the new world of computer connectivity across health care practitioners and providers is another.

Manage the Side Effects of Change

Health care systems exist in a changing world. The environment, organization, economics, capabilities, technology, and regulatory context all change over time. Even the current window of opportunity to improve patient safety is a mechanism for change. And new waves of change are beginning to swell up and move toward shores of health care practices (e.g., reductions to resident work hours). Waves of change are due in part to resource pressures and in part to new capabilities. Uncertainties created by these changes have given rise to public pressures for improving patient safety.

This backdrop of continuous systemic change ensures that hazards and how they are managed are constantly changing. This is important because many of these changes can easily increase complexities of health care delivery. Again, increasing complexity often challenges safety and rarely produces safety benefits without some other investments (Ash, Berg, et al., 2004).

The general lesson is that as capabilities, tools, organizations, and economics change, vulnerabilities to failure change as well—some decay but new forms appear. The state of safety in any system is always dynamic, and stakeholder beliefs about safety and hazard also change. Progress on safety depends on anticipating how these kinds of changes will create new vulnerabilities and paths to failure even as they provide benefits on other scores (Patterson et al., 2002).

For example, new computerization is often seen as a solution to human performance problems. Instead, consider potential new computerization as another source of change. Examine how this change will affect roles, judgments, coordination, and what makes problems difficult. This information will help reveal side effects of the change that could create new systemic vulnerabilities.

Armed with this knowledge, we can address these new vulnerabilities at a time when intervention is less difficult and less expensive (because the system is already in the process of change). In addition, these points of change are opportunities to learn how the system actually functions and sometimes malfunctions.

Another reason to study change is that health care systems are under severe resource and performance pressures from stakeholders. First, change under these circumstances tends to increase coupling, that is, the interconnections between parts and activities, in order to achieve greater efficiency and productivity. However, research has found that increasing coupling also increases operational complexity and increases the difficulty of the problems practitioners can face. Second, when change is undertaken to improve systems under pressure, the benefits of change may be consumed in the form of increased productivity and efficiency and not in the form of a more resilient, robust, and therefore safer system. Thus one linchpin of future success on safety is the ability to anticipate and assess the impact of change to forestall new paths to failure (Rochlin, 1999).

In addition, investments in safety are best timed to coincide with windows of opportunity where change is happening for other reasons as well. A great deal of leverage may result from projects designed to show health care organizations how to take advantage of change points as windows of opportunity where they can rethink processes, work flow, and new modes of collaboration to reduce the potential for breakdowns (Woods & Cook, 2002).

The System of Health Care Delivery Is Changing to Include Patients in New Ways

Patients are becoming involved in their own care (or their family member's care) in new ways. Patients have new access to information, allowing them to take an active role in treatment decisions. Technology and other factors are shifting care from in-patient settings to home settings where patients become a provider of their own treatment (e.g., Klein & Meininger, 2004; Obradovich & Woods, 1996).

Patient self-managed treatment represents a large and growing part of the health care system. Human factors can support patient safety in self-managed treatment. Errors can occur when information and interfaces do not fit the patient's capacities or past experiences or the demands of daily life (Klein, 2003). Human factors can focus attention on underlying mechanisms, behavioral patterns, and contextual contributions and provide the methods and tools to design the support systems that match patient needs (Klein et al., 2004; Porter, Cai, Gribbons, Goldmann, & Kohane, 2004).

Studying Human Performance, Human–Machine Systems, Collaboration, and Organizational Dynamics Requires Methods Unfamiliar to Health Care

Ultimately, the study of human performance is in one sense or another the study of problem solving. Since its origins more than one hundred years ago, understanding problem solving, be it a person, human–machine system, distributed team, or organization, has always been the study of the processes that lead up to outcomes—what is seen as a problem-to-be-solved, how to search for relevant data, how to anticipate future events, how to generate hypotheses, how to evaluate candidate hypotheses, and how to modify plans to handle disruptions.

The base data is the process or the *story* of the particular episode—how multiple factors came together to produce that outcome (Dekker, 2002; Klein, 1998; Klein, Orasanu, Calderwood, & Zsambok, 1995). Patterns abstracted from these processes are aggregated, compared, and contrasted under different conditions—different problem demands (scenarios), different human–human and human–machine teams, different levels of expertise, different external tools.

The fields that study one or another type of problem solving have developed sophisticated methods tailored to meet the uncertainties of studying and modeling these processes. They are deeply foreign to medical research communities, but they are the lifeblood of coming to understand human performance in any complex setting, including health care

(Hoffman & Woods, 2000). Ethnography (Hutchins, 1995), interaction analysis (Jordan & Henderson, 1995), protocol analysis (Ericsson & Simon, 1984), critical incident techniques (Flanagan, 1954; Klein, 1998), and cognitive work analysis (Vicente, 1999) are just a few of the techniques to be mastered by the student of human problem solving at work. (To see some of these techniques in action in health care, see the studies in Nemeth, Cook, & Woods, 2004, and Patterson, Rogers, Chapman, & Render, 2005).

One critical resource for the study of problem solving is mechanisms to build or obtain access to simulation environments at different scopes and degrees of fidelity. Much of the progress in aviation safety has depended on researchers having access to full scope training simulators to study issues such as effective human–human and human–machine cooperation (e.g., Layton et al., 1994). This has occurred through research simulators at NASA Ames and Langley Research Centers, through partnerships with pilot training centers (when research and training goals can be synchronized), and through the use of rapid prototyping tools to create simulation test beds. We have already begun to see how the availability of simulator resources in health care (notably for anesthesia and for the operating room) can be a catalyst to learning about the factors that lead to effective or ineffective human performance (Guerlain et al., 1999; Howard et al., 1992; Nyssen & De Keyser, 1998; Weinger at al., 2004).

Using these resources to understand human performance depends on special skills such as problem or scenario design (the design of the problems that study participants attempt to solve) and in analysis techniques such as interaction and protocol analysis (De Keyser & Samercay, 1998). Health care research organizations will need to create, modify, and use simulation resources to provide critical pieces of evidence in the process of finding effective ways to improve safety for patients.

Technology Evaluation

Evaluating changes intended to improve some aspect of human performance is a difficult problem. Human factors has worked with many industries to assess the impact of technology and other interventions (e.g., training systems) designed to aid human performance. Stakeholders have frequently asked us to give them a simple positive or negative result—does this particular system or technology help significantly or not? We refer to such studies as verification and validation evaluations, or V&V.

Despite the surface appeal of such efforts and the desire to provide definitive answers to guide investments, V&V has proved to be a limited tool in other high-risk domains. The short summary of the lessons is that such studies provide too little information too late in the design process, and at too great a cost.

They provide too little information in a variety of ways. There are multiple degrees of freedom in using new technology to design systems, but V&V studies are not able to tell developers how to use those degrees of freedom to create useful and usable systems. The problem in design today is not the question of whether a certain system can be built, but rather what would be useful to build given the wide array of possibilities new technology provides.

Measurement problems loom large because V&V studies usually try to capture overall outcomes. However, the systems are intended to influence aspects of the processes (human expertise, cooperative work, a culture of safety) that are important to outcomes in particular kinds of situations that could arise (Woods, Cook, & Billings, 1995). As a result, global outcome measures tend to be insensitive to the operative factors in the processes of interest or wash out differences that are significant in restricted kinds of situations.

New systems and technology are not unidimensional, but multifaceted, so that problems of credit assignment become overwhelming. Introducing new technology is not manipulating a single variable, but instead a change that reverberates throughout a system, transforming judgments, roles, relationships, and weightings on different goals (Carroll & Rosson, 1992). This process, called the task-artifact cycle, creates the envisioned world problem for research and design (Dekker & Woods, 1999; Hoffman & Woods, 2000; Woods & Dekker, 2000): How do the results of studies and analyses that characterize cognitive and cooperative activities in the current field of practice inform or apply to the design process, because the introduction of new technology will transform the nature of practice, what it means to be an expert, and the paths to failure? Health care specialists need only consider the many reverberations of the change to laparoscopic surgery or the introduction of new information systems to see these processes play out (e.g., Ash, Gorman, et al., 2004; Cook et al., 1998; Dominguez, Flach, Lake, McKellar, & Dunn, 2004; Patterson et al., 2002; Patterson, Rogers & Render, 2004).

V&V studies occur too late in the design process, especially given their great cost, to provide useful input. By the time the V&V results are available, the design process has committed to certain design concepts and implementation directions. These sunk costs make it extremely difficult to act on what is learned from evaluation studies late in the process. In addition, it is difficult to generalize the results from a single study of one system to other systems at other organizations due to the myriad design and implementation factors that differ between systems, or even from a single study of one system to the same system in a changed environment. (Han et al., 2005; Koppel et al., 2005; Wears & Berg, 2005; Nemeth & Cook, 2005).

The advent of rapid prototyping technology has revolutionized evaluation studies. While late V&V studies still have a role, the emphasis has shifted completely in many different work domains to early, generative techniques such as ethnography, envisioning techniques, and participatory design (Carroll & Rosson, 1992; Greenbaum & Kyng, 1991; Sanders, 2000; Smith et al., 1998). Health care needs to build on this experience and learn the use of these new techniques.

HIGH RELIABILITY ORGANIZATIONS AND REACTIONS TO FAILURE

One of the most productive areas of work on human error in the last 10 years has been about reactions to failure (Dekker, 2002; Rochlin, 1999; Woods et al., 1994). In this work we have come to understand more about what characterizes high reliability organizations (Adamski & Westrum, 2003; Grabowski & Roberts, 1997; Roberts, this volume; Rochlin, La Porte, & Roberts, 1987) and about the common oversimplifications or fallacies about error that block forward progress (Cook et al., 1998; Dekker, 2003; Dekker, 2005).

High-reliability organizations create safety by anticipating and planning for unexpected events and future surprises. These organizations continue to invest in anticipating the changing potential for failure, regardless of past success, because they appreciate that their knowledge is imperfect and that their environment continues to change. The heart of this process is learning activities that depend on open flow of information about the changing threats and about the changing effectiveness of their failure-sensitive strategies. For these organizations, safety is a value, not a commodity.

Escape From Hindsight Bias

There are a variety of factors that block or inhibit the learning processes central to a high-reliability culture. One is the hindsight bias (Fischhoff, 1975; Woods & Cook, 1999; Woods et al., 1994). The hindsight bias is one of the most reproduced research findings relevant to accident analysis and reactions to failure. Knowledge of outcome biases our judgment about the processes that led up to that outcome.

In the typical study, two groups of judges are asked to evaluate the performance of an individual or team. Both groups are shown the same behavior; the only difference is that one group of judges are told that the episode ended in a poor outcome, while other groups of judges are told that the outcome was successful or neutral. Judges in the group told of the negative outcome consistently assess the performance of humans in the story as being flawed in contrast with the group told that the outcome was successful. Surprisingly, this hindsight bias is present even if the judges are instructed beforehand not to allow outcome knowledge to influence their judgment.

Hindsight is not foresight. After an accident, we know all of the critical information and knowledge needed to understand what happened. But that knowledge is not as easily available to the participants before the fact. In looking back, we tend to oversimplify the situation that the actual practitioners faced, and this oversimplification tends to block our ability to see the deeper story behind the label *human error* (Cook et al., 1998; Rasmussen, 1990b; Woods & Cook, 2003).

Researchers use methods designed to remove hindsight bias to see the multiple factors and contributors to incidents, to see how people usually make safety in the face of hazard, and to see systemic vulnerabilities before they contribute to failures (Woods, 2005b). Research has developed a variety of techniques to reduce hindsight bias (Dekker, 2002, 2005). These are available to use and modify as necessary in health care research on safety.

Despite widespread communication about factors that block learning about how safety is created, hindsight and related "biases" continue to plague the literature on adverse events in health care. The studies of injury or death rates as a result of error and virtually all incident review procedures used in health care today fail to control for hindsight bias. This should not be considered acceptable by anyone interested in improving safety. It is time to stop repeating this "error" in the study of error.

Resilience

When research escapes from hindsight, studies reveal the sources of resilience that usually allow people to produce success when failure threatens. Methods to understand the basis for technical work shows how health care workers are struggling to anticipate forms of or 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 (Woods & Cook, 2002, 2003). In other words, 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. Failures occurred against this background when multiple contributors—each necessary but only jointly sufficient—combine. Work processes do not chose 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 (Woods, 2005b). To understand how failure sometimes happens, one must first understand how success is obtained—how people learn and adapt to create safety in a world fraught with gaps, hazards, trade-offs, and multiple goals (Cook et al., 2000).

The theme that leaps out from these results is that failure represents *breakdowns in adaptations* directed at coping with complexity. Success relates to organizations, groups, and individuals who produce *resilient systems* that recognize and adapt to variations, changes, and surprises (Rasmussen, 1990a; Rochlin, 1999; Sutcliffe & Vogus, 2003; Weick, Sutcliffe, & Obstfeld, 1999). Resilience is the ability to adapt or absorb disturbance, disruption, and change, especially to disruptions that fall outside of the set of disturbances the system is designed to handle. The brittleness (which is the opposite of resilience) of some organizations and systems becomes evident when cases of near failure or adverse events are examined using the concepts and methods described in the earlier sections. Cook and O'Connor (2005) and Patterson, Cook, et al. (2004) provide detailed analyses of how brittle systems in health care break down in the face of change and a concatenation of factors. Cook and Rasmussen (2005) provide a basic overview of brittleness and resilience for safety management in health care organizations.

These results have led to the emerging area of resilience engineering as an alternative to error tabulations (Hollnagel, Woods, & Leveson, 2006). Many of the essential constituents of resilience engineering are already at hand as a result of research on organizational risk factors (Adamski & Westrum, 2003; Carthey et al., 2001; Hollnagel, 2004). The initial steps in developing a practice of resilience engineering have focused on methods and tools:

To analyze, measure, and monitor the resilience of organizations in their operating environment.

2. To improve an organization's resilience vis-à-vis the environment.

To model and predict the short- and long-term effects of change and line management decisions on resilience and therefore on risk.

Innovate New Models of Accountability

As the new messages about a systems approach to safety circulated and became more visible in health care, they collided with the common belief that practitioners and managers should be "accountable" to patients and to other stakeholders. But accountability in this common belief is operationalized in terms of pursuit of culprits, threats of disciplinary actions, and threats of stigmatization (Woods, 2005a).

These two trends collide in a basic double bind for the patient safety movement: Blame, even if disguised as accountability, drives out information about systemic vulnerabilities, stops learning, and undermines the potential for improvement (Billings, 1999). The challenge for research is to find a way out of the double bind—How do we create a safe environment for learning about the potential for failure in a publicly accountable system of health care delivery (Sharpe, 2004)?

Accountability is emphasized in the debate on patient safety because how decision makers are held accountable is presumed to influence how they make decisions and the quality of those decisions. Social links such as accountability can be powerful forces influencing human decision making, and these relationships have been studied in organizational dynamics, social cognition, and human–machine interaction (e.g., Hirschhorn, 1993; Lerner & Tetlock, 1999; Ostrom, 1990;

Tetlock, 1999). This information can be integrated with ethical and legal scholarship to stimulate the innovation of new systems for managing accountability relationships (Sharpe, 2000).

Practitioner decision making always occurs in a context of expectation that one may be called to give accounts for those decisions to different parties. How and to whom people expect to be called to account affects their performance in implicit and explicit ways. The expectations for what are considered adequate accounts and the consequences for people when their accounts are judged inadequate are critical parts of the cycle of giving accounts and being called to account (Brown, 2005a).

Interestingly, different factors in this reciprocating cycle can support or undermine practitioner performance and systems learning in predictable ways. Note that, from a behavioral science point of view, accountability is a neutral term that only points to the processes in this cycle of giving and being called to give accounts or reasons for a decision. First, past research shows that there is a complex set of factors, relationships, and effects at work in the reciprocating cycle of calling on and giving of accounts. Second, the empirical regularities and relationships are not consistent with motivational accounts, that is, that accountability creates general improvements by increasing task motivation. Third, and most startling, the research demonstrates that some factors in the reciprocating cycles of accountability may degrade decisions, performance, cooperation, and learning, while other relationships in the cycle may enhance these cognitive processes (Brown, 2005a, 2005b; Ostrom, 2003).

For example, under some conditions, the need to give an account for a decision to others can increase critical thinking and attenuate commitment (presumably ways to enhance the decision), while other conditions can increase self-justification and bolster an initial attitude and commitment (presumably ways that reduce the quality of a decision). Some forms of accountability can increase defensive behavior, create adversarial relationships among parties who need to cooperate, or lead people to prefer options that are easier to justify given knowledge of the standards others impose for giving of suitable accounts (Lerner & Tetlock, 1999).

These results allow us to see the label "culture of blame" in a new way. It is a kind of system of accountability, but it is only one way to design and manage such systems. If one analyzes a "culture of blame" in terms of the dynamics of cycles of accountability, we find many of the factors that have been implicated in degrading performance, cooperation, and learning (Brown, 2005a; Woods, 2005a).

The social cognition research on cycles of accountability clearly captures the complexity of the effects and demonstrates the naïveté of the belief that improving safety only requires holding others accountable. The slogan of "moving beyond a culture of blame" is a call to abandon poor systems of accountability, not an environment where accountability is absent. It is a necessary part of our life as social creatures that we explain our actions to others. The systems approach examines the reciprocating cycle of giving accounts and calling to accounts between the sharp end of practice and the blunt end of organizational context to determine the lawful effects of different systems for accountability (Dekker, 2003).

New work is needed to model and describe systems of accountability and their effects in health care. The results from this work should be used to engage all stakeholders in a process to explore new designs of systems of accountability that will produce the desired effects and advance our common goals.

Create and Share Learning Tools

The research on high-reliability organizations emphasizes continued learning about risks and mitigation strategies. In health care, direct learning and improvement from experience with accidents and incidents has been observed to be very limited and narrow. This appears to be partly because of the fear of blame and litigation. In addition, there are few organizational structures that promote learning about paths to failure.

An important area for new work is creating learning tools that function throughout health care organizations (Adamski & Westrum, 2003). Some believe that expanded requirements for notification of adverse events and near-misses will accomplish this. But lessons from aviation indicate that much more is needed in the analysis of cases and in feedback mechanisms to health care practitioners to complete a cycle of learning based on incident reporting (Billings, 1999). New incident reporting systems will need to encompass much more than new forms to fill out and new notification requirements to be effective. Serious issues remain about whether these programs will be effective, including the independence of the review teams, the need to incorporate human performance expertise in order to recognize deeper patterns, the move to analyze sets of cases rather than one case at a time, how to generate meaningful sustained improvements, and how to provide feedback to practitioners about how what was learned is relevant to them in their area of the world of health care.

The difficulties in learning from accidents and learning before accidents occur are particularly vivid in the contrast between two parallel disasters that played out in 2003—the loss of the Columbia space shuttle and the death of Jesica Santillan, a transplant patient at Duke University Hospital. Both events occurred in February 2003, and two very different processes for understanding and learning from these tragedies played out in parallel over the next few months. The contrast between the two investigations highlights the importance of results on how learning after accidents can break down (see Weick et al., 1999; and chap. 6 of Woods et al., 1994).

An independent and highly distinguished technical panel examined the Columbia accident and NASA as an organization (Columbia Accident Investigation Board, 2003). A wide-ranging and detailed set of information on how to improve the organization resulted from the public and the independent examinations. NASA supported the investigation despite the burden of criticism and is acting on what was learned from the public dissemination of its deficiencies as an organization. Systemic changes are widespread, and the only question is whether these new investments can be sustained over the long term. Plus the lessons are public and can be used by all organizations that manage risky processes under intense production pressures (Starbuck & Farjoun, 2005). During the same time period, the death of a seventeen-year-old girl following mistakes in a transplant procedure at the Duke University Hospital also captured public and news attention.[1] However, little is known publicly about the deeper systemic and organizational contributors to the accident. Press releases by the hospital itself provide most of the available information. The legal, institutional, and professional responses that followed from the tragedy are largely invisible to the public.[2] Little is known publicly about what changes transplant medicine as a whole needs to make and who is monitoring the effectiveness of these changes over time. (but see Wailoo, Livingston & Guarnaccia, 2006).

The comparison of the responses to the two tragedies raises serious questions that health care organizations have not begun to confront adequately. Why are there no *independent* investigations of iatrogenic patient injuries? In no other high-risk system does the organization where the adverse event occurred investigate itself. How are organizations learning about systemic vulnerabilities, developing systemic responses, and monitoring changes over time? Press releases about responses from the affected organization itself are not an effective means to reestablish trust and confidence following serious injuries to patients as a result of care (Cook et al., 1998). Deflecting blame is not a characteristic of high-reliability organizations (Brown, 2005b; Weick et al., 1999)

Interdisciplinary Partnerships

The success of NASA programs in aviation safety was built on interdisciplinary partnerships. The success of safety initiatives in health care is very likely to depend on building the same kinds of partnerships across quite different technical disciplines. Considering patient safety inevitably leads to technical issues about human performance, human–computer cooperation, organizational dynamics, software engineering, and other fields normally considered outside health care. The new research efforts will need to be structured to build up these partnerships between technical areas concerned with different aspects of human performance and different medical and practitioner specialties. One important activity will be to develop a new cadre of experts who are skilled at these interdisciplinary projects.

The success of NASA programs was based on a portfolio of research and development activities that included more basic work on human performance (e.g., mental workload), innovation of new directions for aiding human performance (e.g., cockpit resource management), advanced development, and technology transfer projects. In this process, different kinds of work were carried out and sponsored, including field research, simulator studies, concept development, and evaluation studies. The infrastructure at NASA helped cross-stimulate

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[1] "Lessons from Jesica," February, 24, 2003, *INSIDE: The Duke University Medical Center Employee Newsletter*, 12(4). Retrie 2005 from http://dukemednews.duke.edu/mediakits/detail.php?id=6498#remembered

[2] "Jesica Santillan Remembered," by R. Snyderman & W. J. Fulkerson, February 4, 2004, Duke University Media Kit.

all of these activities around the goal of developing new design directions that would be useful in improving aviation safety. The structure at NASA and NASA's role in the aviation industry provided another essential ingredient for success—independence. The issues underlying safety are potentially controversial. A technically grounded, independent organization whose only purpose is advancing safety can develop a reservoir of technical results and organizational confidence to ride through these controversies with their substantive efforts for safety intact (Woods, 2006).

Health care would do well to study the formal and informal organizational basis of the successes of the NASA Research and Development (R&D) program and to model their own research efforts on patient safety on NASA's human factors programs.

CONCLUSION

We have a window of opportunity for improving safety for patients, but there are many false trails that could consume the energy and resources available. To take advantage of this window we must be prepared to question conventional wisdom and assumptions by building a partnership between different health care specialties and different human performance specialties that intersect at the label *human error*. These human performance specialties are substantive, deep, and unfamiliar to health care. They are the wellspring for techniques, concepts, and systems that will improve human performance in health care, as has been the case in other high-risk domains.

From the past work in human factors, a simple standard emerges for judging success in research on resilience, error and safety. Research is successful to the degree that it helps recognize, anticipate, and defend against paths to failure that arise as organizations and technology change, **before any patient is injured.**

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