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ORIGINAL ARTICLE

Collaborative cross-checking to enhance resilience

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Abstract Resilience, the ability to adapt or absorb disturbance, disruption, and change, may be increased by team processes in a complex, socio-technical system. In particular, collaborative cross-checking is a strategy where at least two individuals or groups with different perspectives examine the others' assumptions and/or actions to assess validity or accuracy. With this strategy, erroneous assessments or actions can be detected quickly enough to mitigate or eliminate negative consequences. In this paper, we seek to add to the understanding of the elements that are needed in effective cross-checking and the limitations of the strategy. We define collaborative cross-checking, describe in detail three healthcare incidents where collaborative cross-checks played a key role, and discuss the implications of emerging patterns.

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1 Introduction

There is a growing consensus that resilience, the ability to adapt or absorb disturbance, disruption, and change, may be increased by team processes in a complex, socio-technical system (Hollnagel et al. 2006; Rasmussen 1990; Weick et al. 1999). The concept of resilience is founded upon the belief that failures are breakdowns in the normal adaptive processes necessary to cope with the complexity of the real world and that success relates to organizations, groups and individuals who produce resilient systems that recognize and adapt to variations, changes and surprises (Rasmussen et al. 1994; Cook et al. 2000; Woods and Shattuck 2002; Sutcliffe and Vogel 2003).

This body of work has led to the emergence of techniques for Resilience Engineering (Hollnagel et al. 2005; Cook and Rasmussen 2005). Resilience Engineering focuses on what sustains or erodes the adaptive capacities of the human–technical system in a changing environment. The focus is monitoring organizational decision making to assess the risk that the organization is operating nearer to safety boundaries than it realizes in response to pressures to be ‘‘faster better cheaper.’’ More generally, an organization has levels of adaptive capacity that needs to meet or exceed a wide range of environmental pressures and demands (Westrum 2006). Studies of how systems are resilient and how breakdowns in resilience occur have begun to show how to measure and improve system safety (e.g., Carthey et al. 2001; Patterson et al. 2002; Woods 2005; Miller and Xiao 2006).

These studies point to collaborative cross-checking as a critical component of resilience because erroneous assessments or actions can be detected quickly enough to mitigate or eliminate negative consequences. Studies of problem detection in aviation and nuclear power both found that mis-assessments of the situation at hand were only corrected when fresh perspectives entered the situation (Woods et al. 1987; Sarter 2000). Problem detection is challenging because it often requires reconceptualizing the situation from a different stance and experience base (Klein et al. 2005; Klein 2006).

The findings regarding the effectiveness of collaborative cross-checking are mixed in the literature. On the positive side, the inclusion of pharmacists during physician rounds was associated with fewer adverse drug events (Leape et al. 1999). Similarly, interdisciplinary rounds with the entire care team in a Surgical Intensive Care Unit (SICU) was associated with decreased mortality, increased patient satisfaction, and increased quality of work life (Uhlig et al. 2002). Cross-checking through machine critiquers in blood banking also enhanced performance even in situations where both the machine advisor and the human practitioner had great difficulties performing alone (Guerlain et al. 1999). On the negative side, routinized cross-checking, particularly when effortful attention is required and the base rate for problems is low, is rarely effective, often referred to as the ‘‘vigilance decrement’’ (Williams 1986). A number of studies have found that having two observers perform a monitoring task does not necessarily lead to improved performance (e.g., Erev et al. 1995). Similarly, handoff strategies are an important concern today because well-designed handoffs can increase resilience whereas poorly designed handover processes can contribute to adverse events (Cooper et al. 1982; Patterson et al. 2004; Behera et al. 2005).

In this paper, we seek to add to the understanding of the elements that are needed in effective cross-checking and the limitations of the strategy. We define collaborative cross-checking, describe in detail three healthcare incidents where collaborative cross-checks played a key role, and discuss the implications of emerging patterns.

2 Distinctions in collaborative cross-checking

Collaborative cross-checking is a strategy where at least two individuals or groups with different perspectives examine the others’ assumptions and/or actions to assess validity or accuracy. These perspectives can differ on a number of dimensions, including goals, responsibilities, functions, authority, stance, expertise, resources, methodologies, and knowledge or information of various types. The primary intent of a collaborative cross-check is to detect an erroneous assessment or action, although a number of other benefits may be realized. Collaborative cross-check interactions incur costs such as interruptions, increased cognitive work, increased complexity resulting from changes to plans, diffusion of responsibility, and coordinative costs such as identifying and scheduling appropriate individuals.

2.1 Scope of change following collaborative cross-checking

A cross-checking interaction can result in changes to activities and outcomes. The anticipated scope of change stemming from a coordination event is largely determined by the relationship between the participating individuals or teams. Distinctions in relationships include:

(1) Asymmetric hierarchy and expertise with similar perspective (e.g., attending physician and resident physician).
(2) Asymmetric expertise, non-hierarchical with similar perspective (e.g., mentor and mentee).
(3) Symmetric expertise with similar perspective:
(a) Same time (e.g., resident physicians reporting to the same attending physician with different patients during the same shift).
(b) Different times (e.g., handoff from resident physician to resident physician).
(c) During escalating situations (e.g., nurse provides aid to another nurse in ‘‘on-call’’ manner).
(4) Functionally distinct, overlapping roles:
(a) Anomalous situations (e.g., code team and nurse).
(b) Situations requiring specialized expertise (e.g., cardiologist physician and internal medicine physician).
(c) Nominal situations (e.g., physician and nurse caring for the same patient).
(5). Weakly defined role relationships
(a) Integration resource (e.g., case manager).
(b) ‘‘Floater’’ resource (e.g., Clinical Nurse Specialist).
(c) Cross-cutting functional resource (e.g., patient safety officer).

Although the extent of receptivity to changes to ongoing and future plans following a cross-checking interaction is somewhat predictable based on these relationships, in practice there is immense variability. People in leadership positions impact social norms for receptivity expectations, whether or not they participate directly in collaborative cross-checks. In addition, individual differences and social relationships contribute to variability.

Note that the actual change and perceived change, often as portrayed in official documentation, following a collaborative cross-check can differ. In many situations, changing a plan following an interaction is positively rewarded. In these cases, the scope of change might be exaggerated in official documentation. In other situations, a large scope of change might imply that prior plans were erroneous, which might negatively impact reputation. In these cases, the actual change may be larger than what is officially documented.

2.2 Short-term and long-term benefits of collaborative cross-checking

The primary intent of a collaborative cross-check is to detect an erroneous assessment or action in the short term. Nevertheless, a number of other benefits may be realized, including improved plans and ‘‘second order’’ adaptations that improve system resilience over the long term.

Regarding improvements to ongoing and future plans, the following short-term benefits could potentially be realized:

(1) reveal hidden assumptions;
(2) clarify goal trade-offs;
(3) explore new regions of a solution space to satisfy competing goals;
(4) identify unintended consequences of actions (‘‘side effects’’);
(5) identify exceptions and ‘‘boundary conditions’’;
(6) identify possible contingencies;
(7) identify information gaps;
(8) identify influential people who might support or obstruct plan.

In addition, coordination might be improved by a collaborative cross-check, even when no erroneous assessments or actions are detected. Short-term coordination benefits may include:

(1) Improved ability to distribute tasks among individuals or groups to reduce redundant efforts and fill gaps in knowledge.
(2) Increased awareness of perspectives of other individuals and groups (i.e., calibrated ‘‘common ground’’).
(3) Increased awareness of others’ needs for information to promote timely information updates and better anticipate interaction requests.
(4) Improved ability to anticipate changes to others’ perspectives when situations change.
(5) Reduced coordination costs for future meetings, such as by improved ability to anticipate scheduling conflicts.

Finally, collaborative cross-checks may prompt investment in long-term system adaptation, ultimately increasing system resilience over a longer period than a single instance. Interestingly, these adaptations may reduce the benefits of individual cross-checking interactions by removing or reducing system-level contributors to erroneous assessments and actions. For example, a hospital might find that calls to rapid response teams (RRTs) to identify which patients are likely to suffer cardiac or respiratory arrest gradually reduce over time. Rather than signaling a reduction in system resilience, however, these reductions could instead indicate a transfer of specialized knowledge from the RRT to the floor nurses, who then require the RRT less frequently. Long-term ‘‘second order’’ benefits of a series of cross-checking interactions might include:

(1) transfer of knowledge across perspectives;
(2) increased ‘‘meta-knowledge’’ of others’ perspectives;
(3) increased ‘‘team identity’’ across previously distinct individuals or groups;
(4) improve coordination across ‘‘stovepiped’’ groups in an organization;
(5) identify ineffective cross-checking strategies;
(6) system and training redesign.

3 Three incidents employing collaborative cross-checks

An extant corpus of approximately 30 voluntarily reported healthcare incidents, collected to explore a broad set of patient safety issues, was reviewed. Three cases were selected on the basis of collaborative cross-checks playing a key role and firsthand experience with the data collection.

3.1 Overview of cases

3.1.1 Case 1: chemotherapy overdose

In the first case (Table 1), an oncology fellow physician erroneously substituted the medication navelbine for

Table 1 Cross-checking interactions during case 1

Cross-checking interaction	Commentary
Attending cross-checks fellow physician (phone):	Successful
Fellow: Plan is the same as an outpatient from the previous week (administering navelbine on a weekly basis)	Possibly routine strategy for senior physician to first ask junior physician for a plan, which is then critiqued
Attending: No, because the prior case was a non-small cell as opposed to a small cell lung cancer case. Plan should be VP-16 (etoposide) 100 mg/m^2 on days 1, 2, 3 and Carboplatin 6 AUC on day 1, to be repeated every 3–4 weeks	Possibly common misconception that small cell and non-small cell cancers are treated similarly
Pharmacist cross-checks oncology fellow physician (phone):	Not successful
Fellow: I will order navelbine at 100 mg/m^2 and Carboplatin 6 AUC to be given today	Embedded in hospital policy is a defense against cross-checking by a pharmacist who does not specialize in chemotherapy
Pharmacist: The hospital policy does not allow initiating new chemotherapy regimens on the weekends	Rationale for the hospital policy is not stated during interaction
Fellow: I discussed the case with the attending and it is critical to administer the medications as quickly as possible	Fellow assumes that attending physician is aware of the policy: therefore assumes that there is no new information from the pharmacist (who has no specialized oncological expertise) that would overturn decision
Pharmacist cross-checks fellow physician (phone):	Not successful
Pharmacist: The package insert says that the standard dose is 30 mg/m^2 for navelbine. Are you sure that you want 100 mg/m^2?	Pharmacist cross-checks using package insert information because pharmacist with chemotherapy expertise was not home
Fellow: Yes	Package insert included that navelbine is administered with Carboplatin
Pharmacist cross-checks fellow physician (phone):	Not successful
Pharmacist: I am giving the medications to the nurse to hang. Are you sure that you want 100 mg/m^2?	Asking the same question again resulted in the same response
Fellow: Yes	New information was not conveyed (many bags required for the dose, nurse asked pharmacist to call again because she was not very familiar with the medication)
Nurse cross-checks fellow physician (phone):	Successful (somewhat)
Nurse: I administered the navelbine. The patient is diaphoretic, short of breath, and hypertensive. Do you want to hold the carboplatin?	New information and suggestion of a specific action (hold medication) prompted a change of plan
Fellow: Yes, hold the carboplatin	Change of plan was later judged poor because side effects are usually managed rather than halting a chemotherapy treatment prior to completion Physician unaware that nurse is relatively inexperienced with chemotherapy medication
Incoming fellow cross-checks fellow physician:	Successful
Incoming fellow (*reviewing patient record*): Navelbine is not the right medication for this diagnosis, it is VP-16 (etoposide)	Person with one additional year of experience detected substitution while reviewing medications in preparation for taking over
Fellow: Discusses impacts, how to respond, discusses recovery plan with attending and incoming fellow, attending informs family	Once detected, easy to recognize erroneous action

the intended etoposide during ordering. The patient had a prolonged hospitalization with severe leucopenia.

3.1.2 Case 2: questionable heparin order

In the second case (Table 2), an order to initiate heparin when a patient was planned to be discharged was questioned, as well as the subsequent decision by an on-call physician to verbally discontinue the order without knowing the rationale for the original order. There were no apparent negative impacts to the patient.

3.1.3 Case 3: erroneously labeled IV bag

In the third case (Table 3), a patient was administered glucose via a bag that was labeled ‘‘bicarb’’. There were several attempts to troubleshoot high glucose levels, which eventually led to detection of the erroneous label. There were no apparent negative long-term impacts to the patient.

Table 2 Cross-checking interactions during case 2

Cross-checking interaction	Commentary
Pharmacy cross-checks physician order (software): Physician order for starting heparin at 18 drops an hour at 6 a.m. today was verified by pharmacy and distributed to the ward	Not successful Routinized cross-checking strategy Same strategy for every medication High false alarm rate Production pressure
Nursing cross-checks physician order (software): Pharmacy-verified physician order for starting heparin at 18 drops an hour at 6 a.m. today was verified by Registered Nurse assigned as primary caregiver to patient during the night shift	Not successful Routinized cross-checking strategy Same strategy for every medication High false alarm rate Typically batch process verification of orders
Patient cross-checks physician order: Patient did not want heparin started because he was going to get a computed axial tomography (CAT) scan and then go home that day. There is a hep-lock and no order for a CAT scan. Night nurse did not hang medication	Not clear No one knows intent behind heparin order Hep-lock order indicates can get heparin Patient reports CAT scan planned No order for CAT scan Nurse does not access physician who wrote order Little support on night shift to answer questions
On-call physician cross-checks physician order: Night nurse called on-call physician who said that he did not know why heparin had been ordered and that it's OK not to give it (but did not cancel the order in the software package)	Not clear On-call physician does not access physician who wrote order Verbal decision not to give heparin does not match written order
Nurse manager cross-checks cancellation of order: Nurse manager asks incoming shift of nurses listening to audiotape: why are they starting heparin on him today? No response from nurses (resolution of discrepancy not observed; unknown if patient should have received heparin)	Not clear Handoff from night nurse to day nurse Nurse manager routinely listens to handoff updates (unusual) Nurse manager asks error checking question Unclear plan or responsibility for resolution

3.2 Collaborative cross-checks in case 1

The first case (Table 1) is a chemotherapy overdose resulting primarily from erroneous substitution of a medication name. The case was collected via a sequence of critical decision method interviews (Klein 1989) conducted individually with the oncology fellow, oncology attending, pharmacist, and nurse. This case is described in detail in Patterson et al. (2004).

3.3 Collaborative cross-checks in case 2

The second case (Table 2) involves a questionable heparin order. This case was collected via direct observation of an acute care nurse.

3.4 Collaborative cross-checks in case 3

The third case involves medication administration by a nurse from an erroneously labeled IV bag. The IV bag was mixed and erroneously labeled at the point of care by a nurse from a previous shift because pharmacy resources were overwhelmed. This case was collected during a critical decision method interview with a Clinical Nurse Specialist.

4 Discussion of emerging patterns for effective cross-checking

Although no strong conclusions can be drawn from three case studies, there are suggestive emerging patterns:

1. Routinized collaborative cross-checks were not very effective:
   (a) *All cases*. Routinized physician and nurse verification of physician orders did not successfully detect erroneous assessments or actions.
2. Some collaborative cross-checks helped to detect and recover from erroneous assessments and actions, but specialized knowledge and interdisciplinary interactions were often involved:
   (a) *Case 1*. Incoming fellow immediately detected erroneous medication order when reviewing the chart, but not the pharmacist or nurse who did not have as much specialized knowledge of oncology as other staff.
   (b) *Case 2*. Patient detected that the order was questionable, but the night nurse, the on-call physician, the next nurse, and the nurse manager could not adequately recover because they did not access the physician who wrote the original order in order to learn the intent.

Table 3 Cross-checking interactions during case 3

Cross-checking interaction	Commentary
Incoming nurse cross-checks outgoing nurse:	Not successful
Outgoing nurse (*face to face report*): Unstable burn patient with care efforts focused on improving respiratory status from smoke inhalation. Patient has been running high glucose levels (~500) for the last 3 h. She has increased the level of insulin about 10 units/h for 10 h to try to get below 400. IV bag is hanging with hand-labeled ''Bicarb''	Focus on respiratory status, not glucose levels
Incoming nurse: Why are you mixing bags by hand?	Unusual method for mixing IV medications detected
Outgoing nurse: Because pharmacy was unable to keep up, I have been mixing by hand bicarbonate and insulin	Slow dose increases add up to large changes over time Fresh perspective triggers suspicion about glucose levels, but not acted on until questioned by CNS
Clinical Nurse Specialist (CNS) cross-checks pharmacists:	Successful (somewhat)
Pharmacy: We are running out of insulin in the main pharmacy. Please alert the units to the problem until they can get additional supplies	Pharmacy recognizes unusual situation but does not detect erroneous substitution
CNS: How did this happen?	Pharmacy ''unable to keep up''
Pharmacy: High usage by the burn patient	Unusual request triggers CNS to get more information CNS cross-checks outside official role
CNS cross-checks nurse:	Successful (somewhat)
CNS: What's going on with your patient?	CNS starts troubleshooting high glucose levels
Nurse: I have been thinking about calling you all day because of the difficulty in managing the glucose levels. I did not call because I saw progress in the glucose falling from 500 to 400 in the last few hours and our care efforts were focused on respiratory status due to smoke inhalation. Since we are not getting progress from the usual protocol steps in managing glucose, can you give me a written plan of action?	CNS not responsible for other time-critical tasks
CNS: OK. She does literature search to confirm that insulin dosage was very high. Arranges team conference with nurse, physicians, pharmacists, and dietitian	
Team troubleshoots unexpected response to high insulin doses:	Successful (somewhat)
Team conference arranged with CNS, nurse, physicians, pharmacists, dietitian. Team cannot identify reason for patient's unexpectedly low response to high insulin dose. Group decision to replace all IV medications and solutions. With no other changes in treatment, patient's glucose falls from 400 to 100 by 6AM the next day. Decided that best explanation was that glucose was erroneously labeled IV bag during hand mixing	Specific error not immediately detected Generic ''restart'' strategy for IV medications/solutions Time lag to detect change in glucose levels Handoff to next nurse before normal levels

(c) *Case 3*. The incoming nurse during the handoff suspected a problem based on the high glucose level, but did not detect the erroneous label. The Clinical Nurse Specialist suspected a problem but was only able to detect the erroneous label following the decision of an interdisciplinary team conference knowledgeable about the specific patient to employ a strategy to replace all medications.

3. Benefits of collaborative cross-checks were not always immediately realized:

(a) *Case 1*. The fellow's decision to hold the carboplatin medication was likely influenced by the cumulative effect of three cross-checks from the pharmacist and one from the nurse.

(b) *Case 3*. The incoming nurse during the handoff suspected a problem based on the high glucose level and had been considering asking for help from the Clinical Nurse Specialist ''all day,'' but the erroneous label was not detected until some time later.

4. Knowledge of ''typical mistakes'' might aid error detection as well as serve as ''red herrings'':

(a) *Case 1*. Fellow and attending knew that it was easy for first year fellows to confuse small cell and non-small cell cancer treatments.

(b) *Case 1*. Pharmacist suspected the wrong dose, which was more common than the wrong drug.

(c) *Case 2*. CNS conducted literature search to verify that insulin dose was higher than used in other cases.

(d) *Case 3*. It is unusual for nurses to mix and label IV bags.
5. Cross-checks were employed by people outside official roles and responsibilities, and who were not consumed by production pressures:
(a) *Case 1*. The pharmacist called the hospital's pharmacist with expertise in chemotherapy even though she was not working or on-call that day.
(b) *Case 2*. The nurse manager overheard the handoff update that described the questionable order. Although listening to handoff updates was a routine strategy for this individual, it is an unusual role for nurse managers in general. She encouraged resolution of the questionable order.
(c) *Case 3*. The Clinical Nurse Specialist (CNS) conducted a series of activities without being asked to do so that ultimately detected the erroneous labeling on the IV bag.
6. Strategies to render processes more observable may increase resilience even when a specific erroneous assessment or action is not detected:
(a) *Case 1*. Senior physician first asked for the fellow physician's plan, critiqued it, and asked the fellow to restate the new plan.
(b) *Case 1*. The incoming fellow physician reviewed new medication orders for all patients after the handoff.
(c) *Case 2*. Nurse manager overheard handoff updates.
(d) *Case 3*. They "restarted" all medications when the team could not explain the unusual patient condition.

Overall, these findings confirm that collaborative cross-checking can enhance system resilience. They also confirm that routinized cross-checking will never detect all erroneous assumptions and actions because the reconceptualization of the problem from another perspective is a cognitively effortful activity and the benefits are not always realized by the person doing the effort. Therefore, a strong reliance on routinized cross-checking to detect erroneous assumptions and actions should not be pursued.

Probably the most important contribution of this research is the finding that specialized knowledge might be required by the individual performing the collaborative cross-check. This finding implies that using automated software or relatively inexperienced or less knowledgeable personnel to perform cross-checks might not be a particularly effective approach.

In order to enhance resilience, these findings suggest two approaches to increase adaptive capacity both before and after a problem is detected. First, personnel with weakly defined roles who are not consumed by production pressures can support collaborative cross-checking and other cognitively challenging sensemaking functions. Second, processes can be rendered more observable either by explicitly communicating the rationale behind a plan and the intent behind an order or by supporting the ability for people in loosely coupled roles to "listen in" on planning discussions, such as by having nurses or pharmacists attend physician rounds.

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References

Behara R, Wears R, Perry S, Eisenberg E, Murphy L, Vanderhoef M, Shapiro M, Beach C, Croskerry P, Cosby K (2005) A conceptual framework for studying the safety of transitions in emergency care. Adv Patient Safety 2309–2321

Brown JP (2005) Ethical dilemmas in healthcare. In: Patankar M, Brown JP, Treadwell MD (eds) Ethics in safety. Cases from aviation, healthcare, and occupational and environmental health. Ashgate, Burlington VT

Carthy J, de Leval MR, Reason JT (2001) Institutional resilience in healthcare systems. Qual Health Care 10:29–32

Cook RI, Render ML, Woods DD (2000) Gaps in the continuity of care and progress on patient safety. Br Med J 320:791–794

Cook RI, Rasmussen J (2005) Going solid: a model of system dynamics and consequences for patient safety. Qual Safety Health Care 14:130–134

de Leval MR, Carthey J, Wright DJ, Farewell VT, Reason JT (2000). Human factors and cardiac surgery: a multicenter study. J Thorac Cardiovasc Surg 119(4 Pt 1):661–672

Cooper JB, Long CD, Newbower RS, et al (1982) Critical incidents associated with intraoperative exchanges of anesthesia personnel. Anesthesiology 56(6):456–461

Dekker SWA (2005) Ten questions about human error: a new view of human factors and system safety. Lawrence Erlbaum, Hillsdale, NJ

Erev I, Gopher D, Itkin R, Greenshpan Y (1995) Toward a generalization of signal detection theory to *n*-person games: the example of two person safety problem. J Math Psychol 39:360–376

Guerlain S, Smith PJ, Obradovich JH, Rudmann S, Strohm P, Smith J, Svirbely J (1996) Dealing with brittleness in the design of expert systems for immunohematology. Immunohematology 12:101–107

Hollnagel E (2004) Barriers and accident prevention. Ashgate Publishing, Aldershot

Hollnagel E, Woods DD, Leveson N (2006) Resilience engineering: concepts and precepts. Ashgate Publishing, Aldershot

Klein GA, Calderwood R, MacGregor D (1989) Critical decision method for eliciting knowledge. IEEE Trans Syst Man Cybern 19(3):462–472

Klein G (2006) The strengths and limitations of teams for detecting problems. Cogn Technol Work (in press)

Klein G, Pliske R, Crandall B, Woods D (2005) Problem detection. Cogn Technol Work 7(1):14–28

Leape L, Cullen DJ, Clapp MD, Burdick E, Demonaco HJ, Erickson JI, Bates DW (1999) Pharmacist participation on physician rounds and adverse drug events in the intensive care unit. JAMA 282:267–270

Miller A, Xiao Y (2006) Multi-level strategies to achieve resilience for an organisation operating at capacity: a case study at a trauma centre. Cogn Technol Work (in press)

Patterson ES, Cook RI, Render ML (2002) Improving patient safety by identifying side effects from introducing bar coding in medication administration. J Am Med Inform Assoc 9(5):540–553

Patterson ES, Roth EM, Woods DD, Chow R, Gomes JO (2004) Handoff strategies in settings with high consequences for failure: lessons for health care operations. Int J Qual Health Care 16(2):125–132

Patterson ES, Cook RI, Woods DD, Render ML (2004) Examining the complexity behind a medication error: generic patterns in communication. IEEE Trans Syst Man Cybern Part A 34(6):749–756

Rasmussen J (1990) The role of error in organizing behavior. Ergonomics 33:1185–1199

Sarter N (2000) Error types and related error detection mechanisms in the aviation domain: an analysis of aviation safety reporting system incident reports. Int J Aviat Psychol 10(2):189–195

Sutcliffe K, Vogus T (2003) Organizing for resilience. In: Cameron KS, Dutton IE, Quinn RE (eds) Positive organizational scholarship. Berrett-Koehler, San Francisco, pp 94–110

Uhlig PN, Brown J, Nason AK, Camelio A, Kendall E (2002) System innovation: concord hospital. Jt Comm J Qual Improv 28(12):666–672

Weick KE, Sutcliffe KM, Obstfeld D (1999) Organizing for high reliability: processes of collective mindfulness. Res Org Behav 21:13–81

Westrum R (2006) A typology of resilience situations. In: Hollnagel E, Woods DD, Leveson N (eds) Resilience engineering. Ashgate, Aldershott, pp 55–67

Williams PS (1986) Processing demands, training, and the vigilance decrement. Hum Factors 28:567–579

Woods DD (2005) Creating foresight: lessons for resilience from Columbia. In: Starbuck WH, Farjoun M (eds) Organization at the limit: NASA and the Columbia disaster. Blackwell

Woods DD, Shattuck LG (2000) Distant supervision—local action given the potential for surprise. Cogn Technol Work 2:86–96

Woods DD, O'Brien J, Hanes LF (1987) Human factors challenges in process control: the case of nuclear power plants. In: Salvendy G (ed) Handbook of human factors/ergonomics. Wiley, New York