The science of human factors: separating fact from fiction

Alissa L Russ, 1,2,3,4 Rollin J Fairbanks, 5,6,7 Ben-Tzion Karsh,*8 Laura G Militello,9 Jason J Saleem,1,2,3,10 Robert L Wears11,12

ABSTRACT

Background Interest in human factors has increased across healthcare communities and institutions as the value of human centred design in healthcare becomes increasingly clear. However, as human factors is becoming more prominent, there is growing evidence of confusion about human factors science, both anecdotally and in scientific literature. Some of the misconceptions about human factors may inadvertently create missed opportunities for healthcare improvement.

Methods The objective of this article is to describe the scientific discipline of human factors and provide common ground for partnerships between healthcare and human factors communities.

Results The primary goal of human factors science is to promote efficiency, safety and effectiveness by improving the design of technologies, processes and work systems. As described in this article, human factors also provides insight on when training is likely (or unlikely) to be effective for improving patient safety. Finally, we outline human factors specialty areas that may be particularly relevant for improving healthcare delivery and provide examples to demonstrate their value.

Conclusions The human factors concepts presented in this article may foster interdisciplinary collaborations to yield new, sustainable solutions for healthcare quality and patient safety.

INTRODUCTION

“Human error in medicine, and the adverse events that may follow, are problems of psychology and engineering, not of medicine.”

Medicine is devoted to human health and healing, but the science behind why errors occur, and how to reduce the likelihood of preventable harm to individuals, are well described in human factors literature. Human factors—a science at the intersection of psychology and engineering—is dedicated to designing all aspects of a work system to support human performance and safety. Human factors, also known as ergonomics, uses scientific methods to improve system performance and prevent accidental harm.

The goals of human factors in healthcare are twofold: (1) support the cognitive and physical work of healthcare professionals and (2) promote high quality, safe care for patients.

Human factors knowledge has been suggested as a promising mechanism with which to improve healthcare delivery, yet this body of knowledge remains largely untapped. The reasons for this are not fully known. Gurses et al8 posit that safety efforts have been sluggish due to the inadequate integration of human factors principles and methods into healthcare. Their article provides valuable recommendations to accelerate the uptake of human factors. In addition, we believe that common misconceptions about human factors may slow the integration of human factors into healthcare and hinder healthcare improvement. The term ‘human factors’ itself can be misleading and may result in fundamental misunderstandings. It appears that several misconceptions about human factors science are beginning to take root in peer-reviewed medical literature.9–16 For example, some papers refer to ‘human factors’, yet point to the ‘failures’ of people as the underlying cause of adverse events or broken healthcare delivery processes, a stance that is contrary to human factors science and counterproductive for advancing patient safety.20, 21

Other literature describe the application of human factors for specific applications or select healthcare audiences.22, 23 The goal of this paper is to provide a general introduction to human
nitive abilities of humans and are resilient to unanticipated events.

**SEPARATING FACT FROM FICTION**

**Fact #1: Human factors is about designing systems that are resilient to unanticipated events.**

Fiction: *Human factors is about eliminating human error.*

In early childhood, most of us learnt that ‘everyone makes mistakes’. Errors are inevitable, and attempting to eliminate human imperfections in healthcare or any other industry is a futile goal. Therefore, human factors experts gather data about human characteristics and human interactions with the work environment to design systems and tools that support physical and cognitive abilities of humans and are resilient to unanticipated events. This includes gathering data on:

- **Human physical characteristics**, for example, anthropometric measurements on the patient population to redesign hospital beds and reduce the risk of patient entrapment.
- **Human cognitive characteristics**, for example, a cognitive task analysis with intensive care unit staff to inform the design of decision support for ventilator settings and reduce the risk of errors.
- **Human interactions with the overall work system**, for example, how procedural policies, work hour restrictions and patient load can be coordinated to mitigate errors during transfers of care. The study of the overall work system is formally known as macroergonomics.

Cognitive engineering is another well-known framework for studying and designing complex systems.

Human factors is a term that could easily be misunderstood to refer to the failures of people. This position, sometimes expressed in terms of ‘the human factor’ or ‘caused by human factors’, is in opposition to human factors science, which attempts to design systems that support human performance and are resilient to unanticipated events. A human factors approach can also foster a culture of safety, promote a learning environment, and encourage the development of a culture where unintentional errors are reported without fear of retaliation and findings are used to improve various system components to yield sustainable change.

**Fact #2: Human factors addresses problems by modifying the design of the system to better aid people.**

Fiction: *Human factors addresses problems by teaching people to modify their behaviour.*

Work systems often create challenges for people. Human factors aims to identify what aspects of work are challenging or made the ‘wrong action’ seem reasonable in context, and modify these aspects of system design to aid people in the workplace and promote safety. This most frequently involves changing technologies, processes, tools and other inanimate work system components.

While it is critical that healthcare professionals and staff have the education and training necessarily to perform their role, training itself is generally a weak safety intervention. Table 1 outlines when training is likely to be effective or ineffective for improving patient safety, and can serve as a guide to patient safety professionals. In general, human factors approaches strive to avoid using training to compensate for poor system design; rather the focus is on redesigning systems, tools and techniques to yield sustainable improvements in safety.

**Table 1** Overview of when training may or may not be appropriate as a human factors approach to improve patient safety

| Training is likely an appropriate human factors approach to patient safety if… | Training is likely an inappropriate human factors approach to patient safety if… |
|---|---|
| A. The goal is for individuals to become familiar with new technologies, tools or devices to learn about the available options and functions (eg, training a physician when s/he is first introduced to an electronic health record; training when first learning how to use laparoscopic tools). Training should include knowledge about strengths and limitations of specific technologies. | A. The goal is for individuals to stop using technologies, tools or devices ‘in the wrong way’. (This is described as the ‘bad apple’ fallacy.) |
| B. It allows individuals to develop and test new techniques or practices evidence-based techniques in a safe, low risk environment (eg, simulation of operating room to practice a team communication technique that has been demonstrated to improve situational awareness). | B. It is an attempt to change innate human characteristics or imperfections (eg, staff meeting to ‘be more vigilant’ unlikely to lead to sustainable safety improvements.) |
| C. It provides a mechanism for individuals to gain experience with specialised techniques that involve sensorimotor skills (eg, performing surgeries and catheter insertions with supervision or in a simulated environment). | C. It is intended to address a type of error that is occurring across multiple people. (This indicates the system design does not match human characteristics and that system changes, not training, are needed.) |
| D. It is used to instantiate knowledge in realistic scenarios, such as to practice or test procedures for emergency situations (eg, rapid response). | D. Individuals have been previously trained about the safety issue(s) and the problem persists. (Additional training is unlikely to be effective. The phenomenon above indicates there is an issue with other system components.) |
| E. Other system components are considered first, redesigned, and addressed using human factors expertise and principles and no other system changes can possibly be made. | E. Training is the only safety intervention or the primary intervention used, especially when other system components have not been carefully considered and modified first. |
human factors can also provide valuable input on training, particularly in the context of improving team processes and interactions. In these instances, sophisticated training programmes are often developed, and tend to include goals such as increasing awareness about human characteristics (eg, the potential impact of and strategies for avoiding fatigue, stressors, and cognitive overload); practicing sensorimotor skills or new techniques through experiential simulations; and providing trainees with a broad range of experience in a simulated environment to enhance the system’s resilience to unanticipated events.\(^{32} 40 41\)

Understandably, ‘human factors’ can sometimes be mistakenly \textit{equated} with ‘training’ or ‘non-technical skills’ and confused with strategies that are intended to change human behaviour. For example, a recent slide set by The Joint Commission lists ‘human factors’ as one of the root causes of sentinel event data, and portrays it as a set of issues typically associated with human resource management such as ‘... in-service education, competency assessment, staff supervision, resident supervision, medical staff credentialing/privileging...', and other descriptors that are not aligned with human factors science.\(^42\) When a review of a patient safety event leads to a determination that the cause is ‘human error’, it is not uncommon for healthcare organisations to try and modify the behaviour of the individual or group through counsel or retraining, an approach which has been referred to as the ‘bad apple’ fallacy.\(^{35} 36\) Rather than correcting human behavior, human factors approaches focus on improving system design.\(^3 43\) With this approach, deeper investigation into ‘human error’ often uncovers opportunities to improve technology design, organisational structures or procedures.\(^24\)

Fact #3: Human factors work ranges from the individual to the organisational level.

Fiction: \textit{Human factors is focused only on individuals.}

Individual-level human factors research in healthcare has included the redesign of electronic health records, computerised provider order entry systems, bar code medication administration systems, workstations and laparoscopic tools to support healthcare professionals.\(^4\)\(^ 44\) However, human factors work is not limited to the individual level, but ranges from individual to organisational levels, and thus can bring other potential contributions to healthcare. Human factors approaches can examine how the performance and safety of individuals and teams are impacted by organisational design, policies and procedures. For example, this may include:

\begin{itemize}
  \item Developing techniques to facilitate closed-loop communication and situation awareness across teams.\(^ {2 32}\)
  \item Understanding how organisational decisions for equipment purchases impact the performance of clinicians that use the equipment. For example, a hospital may purchase infusion pumps based on the needs of anaesthesiologists in the operating room, and then distribute them for use throughout the hospital. The pumps were designed to be at eye level for a sitting user, but in the emergency department, they are mounted on bedrails at the user’s waist level. The change in viewing position leads to ‘erroneous’ key pressing, and a 100-fold overdose of a vasoactive medication.\(^{45}\)
  \item Evaluating how organisational or national level policies can filter down to affect clinician workload and patient safety. For example, to accelerate patient care timelines, a national VA directive mandates that specialists address electronic consult requests from primary care providers within 7 days. To meet the mandated timeline and avoid penalisation, specialists often deny consults that lack key information, restarting the clock on the performance tracking system. To proceed with the consult, the requesting provider must re-enter all of the information again. Thus, the policy, in combination with other aspects of the system design, increases clinician workload, and can potentially impact patient safety by delaying patient diagnosis and treatment (eg, colonoscopy/colon cancer).\(^{46}\)

Efforts focused on designing systems to support individuals in their work environment are important and necessary. However, much work is also needed to ensure that broader organisational components are effectively designed and coordinated to achieve the desired outcomes.

Fact #4: Human factors is a scientific discipline that requires years of training; most human factors professionals hold relevant graduate degrees.

Fiction: \textit{Human factors consists of a limited set of principles that can be learnt during brief training.}

Many core human factors methods involve qualitative techniques, such as interviews and observations, which appear to be simple and easy. Similarly, the best, most elegant human factors solutions to problems often seem simple in hindsight: after a problem has been reframed in a novel and constructive way. This apparent simplicity belies the expertise required to understand a work domain, its goals and constraints. Human factors expertise cannot be rapidly acquired by means of a brief workshop or seminar, and attempting to apply human factors techniques without proper training and experience is likely to be ineffective\(^ {13}\) or lead to incomplete or misleading analyses and interventions. In some cases, human factors concepts and methods have been misrepresented in the literature. For example, a recent article conducted a closed-ended survey of healthcare professionals, along with a retrospective chart review, in an effort to identify systems factors that contribute to errors in emergency departments.\(^ {47}\) Although the article claims to be in accordance with human factors principles, the methodologies overlook many key system factors that would typically be included in a human factors analysis, such as how the design of technologies and contextual interactions in the system contribute to
adverse events. The article discussion implies that more nurses are needed to intercept errors. This conclusion places the burden on people to prevent harm, rather than redesigning system components to promote safer care.

Through the week-long course, Systems Engineering Initiative for Patient Safety, offered by faculty at the University of Wisconsin-Madison, over 300 physicians, nurses, pharmacists and vendor staff have received training on human factors principles for patient safety and health information technology. This type of intensive training enables health professionals and human factors experts to work together in an advanced and substantive manner. Healthcare professionals can help human factors experts understand what is (and is not) clinically meaningful, while human factors experts can bring new theories and methods to the work of improvement. Ideally, partnerships are formed during the early stages of project development to promote success. Improving the safety and effectiveness of care by means of human factors methods will require the development of substantive, long-term partnerships between human factors and healthcare communities.

Fact #5: Human factors professionals are bound together by the common goal of improving design for human use, but represent different specialty areas and methodological skills sets.

Fiction: Human factors scientists and engineers all have the same expertise.

Similar to the field of medicine, human factors professionals receive general human factors training, but often specialise in a particular human factors domain. Human factors draws upon knowledge of engineering and psychology; thus, fundamental human factors training is most commonly offered by industrial and systems engineering or psychology departments. The majority of individuals with human factors expertise receive training at the graduate level, although some exceptions include a few undergraduate programmes and postdoctoral fellowship training programmes. A human factors specialisation is most commonly acquired through a variety of coursework and pursuit of industrial and systems engineering specialisations.

Table 2  Some of the human factors focus areas that are applicable to healthcare

| Specialisation            | Description                                                                 | Example for healthcare                                                                 |
|---------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Ageing                    | Human factors applications to meet the needs, capabilities, and limitations of the elderly and other special populations | Applying human factors principles to reduce inpatient falls48                            |
| Augmented cognition       | "Development and application of real-time physiological and neurophysiological sensing technologies that can ascertain a human’s cognitive state while interacting with computing-based systems" | Designing tools that can transmit feedback to the surgeon to improve laparoscopic grasp control49 |
| Cognitive engineering and decision making | "Research on human cognition and decision making and the application of this knowledge to the design of systems and training programmes" | Identifying cues and strategies experienced nurses use to recognise infants at risk for sepsis and necrotising enterocolitis to guide the design of training and decision support51 52 |
| Communication             | Human-to-human communication, especially when mediated by technology       | Comparing the information accuracy of manual versus electronic patient status boards in emergency departments53 |
| Human performance modelling | "Development and application of predictive, reliable and executable quantitative models of human performance" | Model-based simulations to investigate how and why age and localised muscle fatigue affect postural control and fall risks54 |
| Industrial ergonomics     | "Application of ergonomics data and principles for improving safety, productivity and quality of work in industry" | The design of a workstation for radiologists using appropriate ergonomic and biomechanics data |
| Macrogenericism           | "Organisational design and management issues in human factors and ergonomics as well as work system design and human-organisation interface technology" | Evaluating system components at various organisational levels (eg, drug route; nurse to patient ratios; medication administration policies) and modifying them in a coordinated manner to aid safe medication administration during shift change55 |
| Perception and performance | "Perception and its relation to human performance"                         | Designing and evaluating visual, audio and combined displays for anesthesiologists56 |
| Product design            | "Developing consumer products that are useful, usable, safe and desirable"  | Redesigning epinephrine autoinjectors for patients in an effort to reduce injection errors during anaphylaxis57 |
| Safety                    | "Development and application of human factors technology as it relates to safety" | Integrating human factors principles into the design of a kit for central line insertion to reduce cognitive burden for healthcare workers, promote best practices and prevent infections58 |
| Training                  | "Training system design and evaluation, innovative technologies for training, and instructional design and implementation" | Developing evidence-based practices for debriefing medical teams, as a mechanism for training and the development of a learning environment59 |
| Usability                 | Measurement of the quality of a user’s experience when interacting with a product or system | Comparative, usability evaluation with clinicians to assess two different designs for computerised clinical reminders60 |

Unless otherwise noted, descriptions, including those in quotations, are derived from the Human Factors and Ergonomics Society Technical Groups.50
of a master’s thesis or doctoral dissertation. Each university tends to emphasise particular areas of the discipline, based on the strengths of the human factors faculty at that institution. This results in human factors professionals who possess different specialised knowledge and methodological skill sets.

Table 2 outlines some of the specialised focus areas within human factors that may be useful in collaborations aimed at healthcare safety and improvement. While some larger healthcare organisations may find it feasible and beneficial to develop a human factors office or department, we recognise that this is not practical for many hospitals. Gurses et al provide several recommendations to build human factors capacity in healthcare. In addition, healthcare stakeholders may find it helpful to target human factors specialty areas that are most aligned with their organisational goals when recruiting for a position or developing collaborations.

For instance: hospitals that want to improve overall quality of patient care may seek expertise in macroergonomics; hospitals with a dearth of safety expertise could consider human factors professionals with expertise in safety; and commercial vendors of devices and technologies may benefit from expertise in product design and/or usability. The specialisations in table 2 are not as distinct and differentiated as those found in the practice of medicine, and there are cases where one individual may have expertise in two or three areas. While all human factors scientists strive to improve work systems for human performance and safety, human factors professionals acquire different skill sets that they can bring to healthcare improvement.

**SUMMARY**

Human factors is an established body of science that is positioned to assist with the challenge of improving healthcare delivery and safety for patients. Human factors and healthcare professionals can work together to identify problems and solutions that may not be apparent by traditional means. While human factors does not promise instant solutions for healthcare improvement, it can provide a wealth of scientific resources for sustainable progress. Here, we have attempted to clarify the goals of human factors and pave the way for interdisciplinary collaborations that may yield new, sustainable solutions for healthcare quality and patient safety.

**Author affiliations**

1Veterans Affairs (VA) Health Services Research and Development Center on Implementing Evidence-Based Practice, Roudebush VA Medical Center, Indianapolis, Indiana, USA
2Regenstrief Institute, Inc., Indianapolis, Indiana, USA
3Indiana University Center for Health Services and Outcomes Research, Indianapolis, Indiana, USA
4Department of Pharmacy Practice, Purdue University College of Pharmacy, West Lafayette, Indiana, USA
5National Center for Human Factors Engineering in Healthcare, MedStar Institute for Innovation, Washington DC, USA
6Department of Emergency Medicine, Georgetown University, Washington DC, USA
7Department of Industrial and Systems Engineering, University at Buffalo, Buffalo, New York, USA
8Departments of Industrial and Systems Engineering, Family Medicine, and Population Health Sciences, University of Wisconsin-Madison, Madison, Wisconsin, USA
9Applied Decision Science, LLC, Dayton, Ohio, USA
10Department of Electrical and Computer Engineering, IUPUI, Indianapolis, Indiana, USA
11Department of Emergency Medicine, University of Florida, Jacksonville, Florida, USA
12Clinical Safety Research Unit, Imperial College London, London, UK

**Acknowledgements** In Memoriam: We wish to dedicate this article to Ben-Tzion ‘Bentsi’ Karsh, PhD (1971–2012), a human factors engineer who was internationally known for his macroergonomics work on healthcare and patient safety. Dr Karsh contributed to the conception and drafting of the initial manuscript for this article. He was a mentor, colleague and friend who will be greatly missed.

**Contributors** All authors contributed to the conception of the paper. AR coordinated the writing, led revisions, and drafted tables 1 and 2. Each author drafted a section of the original manuscript and provided critiques of the intellectual content to produce the final version of the paper.

**Funding** This work was supported in part by the VA HSR&D Center of Excellence on Implementing Evidence-Based Practice, Center grant #HFP 04-148, VA HSR&D PPO# 09-298 and ARHQ grant R18 HS017902. Dr Fairbanks is supported by a NIH Career Development Award from the National Institute of Biomedical Imaging and Bioengineering (K08-EB009090). Dr Saleem is supported by a VA HSR&D Research Career Development Award (CDA 09-024-1).

**Competing interests** None.

**Disclaimer** The views expressed in this article are those of the authors and do not necessarily reflect the position or policy of the Department of Veterans Affairs or the USA government.

**Provenance and peer review** Not commissioned; internally peer reviewed.

**Open Access** This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 3.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/3.0/

**REFERENCES**

1 Senders JW. Chapter 9: Medical devices, medical errors, and medical accidents. In: Bogner MS, eds. Human error in medicine. Hillsdale, NJ: Lawrence Erlbaum Associates, 1994: 159–77.
2 Scanlon MG, Karsh BT. Value of human factors to medication and patient safety in the intensive care unit. Crit Care Med 2010;38(6 Suppl):S90–6.
3 Karsh BT, Holden RJ, Alper SJ, et al. A human factors engineering paradigm for patient safety: designing to support
the performance of the healthcare professional. Qual Saf Health Care 2006;15(Suppl 1):i59–65.

4 Salem J, Russ AL, Sanderson P, et al. Current challenges and opportunities for better integration of human factors research with development of clinical information systems. Yearb Med Inform 2009;48–58. [pii][Published Online First: Epub Date] doi:me09010048

5 Kohn LT, Corrigan J, Donaldson MS. To err is human: building a safer health system. Washington, D.C.: National Academy Press, 2000:13–14.

6 Reid PP, Compton WD, Grossman JH, et al. Building a better delivery system: a new engineering/health care partnership. Washington, DC: National Academy of Engineering and Institute of Medicine, 2005.

7 Valdez RS, Ramly E, Brennan PF. Industrial and systems engineering and healthcare: critical areas of research. Rockville, MD: Agency for Healthcare Research and Quality, 2010:97.

8 Gurses AP, Ozok AA, Pronovost PJ. Time to accelerate integration of human factors and ergonomics in patient safety. BMJ Qual Saf 2012;21:347–51.

9 Ros J. Considering the human factors in patient safety. J Perinat Neonat Nurs 2009;24:55–6.

10 Liberman A, Buckingham B, Phillip M. Diabetes technology and the human factor. Int J Clin Pract 2011;65(Suppl 170):83–90.

11 Rosenstein AH, O’Daniel M. Impact and implications of disruptive behavior in the perioperative arena. J Am Coll Surg 2006;203:96–105.

12 Kastner M, Estey E, Perrier L, et al. Understanding the relationship between the perceived characteristics of clinical practice guidelines and their uptake: protocol for a realist review. Implement Sci 2011;6:69.

13 Cahan MA, Larkin AC, et al. Transforming the culture of surgical education: promoting teacher identity through human factors training. Arch Surg 2011;146:830–4.

14 Morgan PJ, Kurrek MM, Bertram S, et al. Nontechnical skills assessment after simulation-based continuing medical education. Simul Healthc 2011;6:253–9.

15 Bleetman A, Sanusi S, Dale T, et al. Human factors and error prevention in emergency medicine. Emerg Med J 2012;29:389–93.

16 Cahan MA, Larkin AC, Starr S, et al. A human factors curriculum for surgical clerkship students. Arch Surg 2010;145:1151–7.

17 Baysari MT, Beckmann MH, Li L, et al. Failure to utilize functions of an electronic prescribing system and the subsequent generation of ‘technically preventable’ computerized alerts. J Am Med Inform Assoc 2012;19:1003–10.

18 Fabri PJ, Zayas-Castro JL. Human error, not communication and systems, underlies surgical complications. Surgery 2008;144:577–63; discussion 63–5.

19 Abrams H, Carr D. The human factor: unexpected benefits of a CPOE and electronic medication management implementation at the University Health Network. Healthc Q 2005;8 Spec No:94–8.

20 Russ AL, Weiner M, Saleem JJ, et al. When ‘technically preventable’ alerts occur, the design—not the prescriber—has failed. J Am Med Inform Assoc 2012;19:1119.

21 Karsh BT, Wiegmann D, Wetternack T, et al. Communication and systems factors might still underlie surgical complications. Surgery 2009;145:686–7.

22 Patel VL, Kaufman DR. Medical informatics and the science of cognition. J Am Med Inform Assoc 1998;5:493–502.

23 Zhang J. Human-centered computing in health information systems part 2: evaluation. J Biomed Inform 2005;38:173–5.

24 Dekker S. Patient safety: a human factors approach. Boca Raton, FL: CRC Press, 2011.

25 Guidance for Industry and FDA Staff: Hospital Bed System Dimensional and Assessment Guidance to Reduce Entrapment. U.S. Department of Health and Human Services, Food and Drug Administration, Center for Devices and Radiological Health, 2006.

26 Baxter GD, Monk AF, Tan K, et al. Using cognitive task analysis to facilitate the integration of decision support systems into the neonatal intensive care unit. Artif Intell Med 2005;35:243–57.

27 Karsh BT, Brown R. Macroergonomics and patient safety: the impact of levels on theory, measurement, analysis and intervention in patient safety research. Appl Ergon 2010;41:674–81.

28 Nemeth CP, Cook RI, Woods DD. The messy details: insights from the study of technical work in health care. IEEE Trans Syst Man and Cybern 2004;34:689–92.

29 Vicente KJ. From patients to politicians: a cognitive engineering view of patient safety. Qual Saf Health Care 2002;11:302–4.

30 Szekendi MK, Barnard C, Creamer J, et al. Using patient safety morbidity and mortality conferences to promote transparency and a culture of safety. Jt Comm J Qual Patient Saf 2010;36:3–9.

31 Hollnagel E, Woods DD. Joint cognitive systems: Foundations of cognitive engineering. Boca Raton, FL: CRC Press, 2005.

32 Wright MC, Taekman JM, Endsley MR. Objective measures of situation awareness in a simulated medical environment. Qual Saf Health Care 2004;13(Suppl 1):i65–71.

33 Woods DD, Roth EM. Cognitive engineering: human problem solving with tools. Hum Factors 1998;30:415–30.

34 Pliske RM, Mcloskey MJ, Klein G. Decision skills training: facilitating learning from experience. In: Salas E, Klein G, eds. Linking expertise and naturalistic decision making. Mahwah: Erlbaum., 2001:37–53.

35 Karsh BT, Weinger MB, Abbott PA, et al. Health information technology: fallacies and sober realities. J Am Med Inform Assoc 2010;17:617–23.

36 Dekker S. The field guide to understanding human error. Burlington, VT: Ashgate Publishing Company, 2006.

37 Klein G, Wolf S. Decision-centered training. Proc Hum Factors Ergon Soc 1995;39:1249–52.

38 Karwowski W. Ch 1: the discipline of ergonomics and human factors. In: Salvendy G. Handbook of human factors and ergonomics. 3rd edn. Hoboken, New Jersey: John Wiley and Sons, Inc., 2006: 889–911.

39 Salas E, Wilson KA, Priest HA, et al. Ch 18: design, delivery, and evaluation of training systems. In: Salvendy G. Handbook of human factors and ergonomics. 3rd edn. Hoboken, New Jersey: John Wiley and Sons, Inc., 2006: 477.

40 Marshall DA, Manus DA. A team training program using human factors to enhance patient safety. AORN J 2007;86:994–1011.

41 Guerlain S, Adams RB, Turrentine FB, et al. Assessing team performance in the operating room: development and use of a “black-box” recorder and other tools for the intraoperative environment. J Am Coll Surg 2005;200:29–37.

42 Sentinel Event Data Root Causes by Event Type 2004-Second Quarter 2011. The Joint Commission. http://www.jointcommission.org/.../sc_root_cause_event_type_2004_2q2011.pdf 2011 (accessed 4 Oct 2012).

43 Render ML. Research and redesign are safer than warnings and rules. Crit Care Med 2004;32:1074–5.
44 Van der Putten EPW, Van den Dobbelsteen JJ, Goossens RHM, et al. The effect of augmented feedback on grasp force in laparoscopic grasp control. *IEEE Trans Haptics* 2010;3:280–91.

45 Secondary U.S. Food and Drug Administration. Manufacturer and User Facility Device Experience (MAUDE) Adverse Event Report. http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfmaude/detail.cfm?mdrfoi__id=2139065 (accessed 7 Jul 2012).

46 Saleem JJ, Russ AL, Neddo A, et al. Paper persistence, workarounds, and communication breakdowns in computerized consultation management. *Int J Med Inform* 2011;80:466–79.

47 Camargo CA Jr, Tsai CL, Sullivan AF, et al. Safety climate and medical errors in 62 US emergency departments. *Ann Emerg Med* 2012;60:555–63 e20.

48 Lemaster CH, Wears RL. Stepping back: why patient safety is in need of a broader view than the safety climate survey provides. *Ann Emerg Med* 2012;60:564–6.

49 Russ AL, Militello LG, Saleem JJ, et al. Human Factors Education for Healthcare Audiences: Ideas for the Way Forward. “Human Factors Education for Healthcare Audiences: Ideas for the Way Forward”, Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting Sept 2011: 808–12.

50 Hignett S. Technology and building design: initiatives to reduce inpatient falls among the elderly. *Health Environments Res Des (HERD)* 2010;3:93–105.

51 Crandall B, Getchell-Reiter K. Critical decision method: a technique for eliciting concrete assessment indicators from the intuition of NICU nurses. *ANS Adv Nurs Sci* 1993;16:42–51.

52 Militello L, Lim L. Patient assessment skills: assessing early cues of necrotizing enterocolitis. *J Perinat Neonatal Nurs* 1995;9:42–52.

53 Patterson ES, Rogers ML, Tomolo AM, et al. Comparison of extent of use, information accuracy, and functions for manual and electronic patient status boards. *Int J Med Inform* 2010;79:817–23.

54 Qu X, Nussbaum MA, Madigan ML. Model-based assessments of the effects of age and ankle fatigue on the control of upright posture in humans. *Gait Posture* 2009;30:518–22.

55 Sanderson PM, Watson MO, Russell WJ, et al. Advanced auditory displays and head-mounted displays: advantages and disadvantages for monitoring by the distracted anesthesiologist. *Anesth Analg* 2008;106:1787–97.

56 Guerlain S, Hugine A, Wang L. A comparison of 4 epinephrine autoinjector delivery systems: usability and patient preference. *Ann Allergy Asthma Immunol* 2010;104:172–7.

57 Bakdash JZ, Drews FA. Using knowledge in the world to improve patient safety: designing affordances in health care equipment to specify a sequential “Checklist”. *Hum Factors Ergon Manufacturing Serv Industries* 2012;22:7–20.

58 Salas E, Klein C, King H, et al. Debriefing medical teams: 12 evidence-based best practices and tips. *Jt Comm J Qual Patient Saf* 2008;34:518–27.

59 Usability Basics. Secondary Usability Basics. http://usability.gov/basics/index.html (accessed 25 Jun 2012).

60 Human Factors and Ergonomics Society (HFES) Web Site. “Technical Groups”. Secondary Human Factors and Ergonomics Society (HFES) Web Site. “Technical Groups”. https://www.hfes.org/web/TechnicalGroups/descriptions.html (accessed 7 Dec 2012).

61 Kneebone R. Total internal reflection: an essay on paradigms. *Med Educ* 2002;36:514–18.

62 Kneebone RL. Crossing the line: simulation and boundary areas. *Simul Healthc* 2006;1:160–3.

63 Wears RL, Kneebone RL. The problem of orthodoxy in safety research: time for a reformation. *Ann Emerg Med* 2012;60:580–1.