Health Informatics

Vimla L. Patel
David R. Kaufman
Trevor Cohen *Editors*

Cognitive Informatics in Health and Biomedicine

Case Studies on Critical Care, Complexity and Errors

Springer

Health Informatics

Vimla L. Patel • David R. Kaufman • Trevor Cohen
Editors

Cognitive Informatics in Health and Biomedicine

Case Studies on Critical Care, Complexity and Errors

Springer

Editors
Vimla L. Patel
New York Academy of Medicine
New York, NY
USA

Trevor Cohen
University of Texas
Health Science Center
Houston, TX
USA

David R. Kaufman
Arizona State University
Scottsdale, AZ
USA

ISBN 978-1-4471-5489-1 ISBN 978-1-4471-5490-7 (eBook)
DOI 10.1007/978-1-4471-5490-7
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2013956008

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To Walter Kinstch and Robert Glaser
Who inspired me to push the boundaries
of my thought,
but to do so with style and grace

–Vimla L. Patel

Foreword

In 2000 the James S. McDonnell Foundation initiated a program to support research on complex systems. The purpose of the program is to develop new methods and mathematical tools for advancing complexity science. The particular problem area in which the tools and methods are developed, while not irrelevant, is of secondary interest. However, when a project emerges that combines methodological advances with the promise of addressing a pressing social problem, Foundation support is even more appropriate. This was the case for the proposal submitted to the Foundation by Dr. Vimla Patel and her collaborators – Cognitive Complexity and Error in Critical Care, ER, and Trauma. The research presented in this volume was principally supported by a five-year grant awarded by the McDonnell Foundation beginning in 2007.

The project was funded as a collaborative activity which requires that the funds be used to support the work of a multidisciplinary, multi-institutional team. The grants are intended to encourage collaboration on new or persisting problems that might benefit from being viewed from a new, multidisciplinary perspective. Often the initial years of the grant support the cross-disciplinary discussions and deliberations that are required to develop a new research agenda. Those deliberations developed rapidly among the project collaborators, allowing, as the following chapters attest, a significant body of research to be completed during the first five years of the grant.

As mentioned in the chapters, the stimulus to develop a new research program on the problem of medical errors was the 1999 Institute of Medicine report.

To Err is Human

This report documented the tens of thousands of deaths annually in the United States attributable to preventable medical errors. Medical errors cause more deaths each year than motor vehicle accidents, breast cancer, or HIV. The Institute's report resulted in an unprecedented focus of attention on the problem of errors in medical practice. Even so, follow-up studies by other organizations have found only modest improvements in patient safety since the report's publication.

Cognitive Complexity and Error in Critical Care, ER, and Trauma brings the perspectives of cognitive informatics, complexity science, and clinical practice to bear on the problem of medical errors. Cognitive informatics, a field with its roots in cognitive psychology, provides a framework and methods for understanding and modeling human cognition and behaviors, particularly in technology-mediated environments. In such environments, information flow and human limitations on information processing are fundamental to successful functioning. Research in cognitive informatics is applied in the design of better information and communication systems that enhance rather than impede human cognition.

A most elegant introduction to complexity science is the brief, reader-friendly volume *Thinking in Systems*: *A Primer* (1993) by Donella Meadows. She writes: "A system is an interconnected set of elements that is coherently organized in a way that achieves something." A system consists of elements, interconnections among the elements, and a function or purpose. As one often hears, a system is more than the sum of its parts and as Meadows states, "it may exhibit adaptive, dynamic, goal-seeking, self-preserving, and sometimes evolutionary behavior." Many interconnections between system elements are flows of information or signals connecting decision or action points in the system. The importance of information flow in a system renders systems science and cognitive informatics, the study of human information processing, highly complementary in understanding a complex system, such as an emergency room or intensive care unit.

These complementary disciplines are well suited to provide answers to the fundamental research question: Why does medical error seem resistant to correction? The reason is that these errors arise within highly complex medical care systems. The traditional culture of medicine holds that individuals are responsible when mistakes occur and it is sensible to look for and blame error on a single individual. In fact, medical error is rarely the result of the actions of a single person. If error reduction methods are focused on identifying, blaming, and correcting the individuals responsible for errors, it is not surprising that conventional approaches to error reduction have resulted in at best minimal gains. Thinking in systems points to a different strategy to error. The traditional approach fails because the settings in which errors occur are complex systems. As Meadows points out, some of the most serious and intractable problems arise not from external causes, but are rooted in the internal structure of the complex system. The solutions to these problems will not yield to identifying and blaming the individuals responsible, they will only yield to solutions when we can see the system as the source of its own problems. Its structure can generate errors. Solving the problem requires understanding the system and restructuring it; it requires understanding and restructuring information flow within the system. Cognitive science, and its cousin cognitive informatics, can tell us about the processing capabilities of the system elements, and complexity science can tell us about the effects of sub-optimal versus optimal information-bearing interconnections within the system. The work presented here thus combines two ideas, the importance of understanding how errors occur in a complex system and the need to understand the cognitive demands of medical decision making. Human error will always be a factor, but errors arising out of recurring systemic weaknesses are amenable to intervention, mitigation, and correction.

The work reported in this volume begins to develop methods and approaches that will allow us to apply both systems thinking and cognitive science to address the problem of medical errors. The research is presented as organized around three themes. The first theme emphasizes the cognitive processes that underlie decision-making in critical care, how errors are generated, and how a system can recover from errors. One might say this research looks at the elements of the complex system. The second research theme addresses team interactions and clinical workflow, and the ways in which the unpredictable nature of these interactions may affect patient safety. One might say this research examines the interconnections within the system. The third theme is concerned with issues pertaining to the generation of interventions to improve patient safety, based on the improved understanding of the system's elements and inter-connections. One might say this work addresses the purpose or goal of the complex system that provides medical care.

As for the clinical medicine perspective, one of the strengths of this collaborative project was the inclusion of expert medical practitioners, such as Dr. Timothy Buchman and his colleagues, who kept the work grounded in the realities of practice and facilitated interactions between cognitive scientists and clinicians in the medical workplace. Hospitals and clinicians in Phoenix, Houston, St. Louis, Atlanta and New York made profound contributions to the work reported here. Thanks to this involvement, research-based changes in clinical practice and changes in medical training for work in high-risk settings have been developed, evaluated, and refined.

The initial findings and results of this new research program are encouraging. We can expect further advances and as research is translated into practice, a reduction in medical error and improved patient outcomes.

John T. Bruer, PhD, President
Department of Philosophy
Washington University in St. Louis
St. Louis, MO
USA

Reference

Meadows DH. Thinking in systems: a primer. White River Junction, Vermont: Chelsea Green Publishing; 1993.

Preface

Early in my career, I became fascinated with the area of Cognition and Education, influenced heavily by my interactions with my mentors and colleagues, such as Guy Groen, Carl Frederikson, Walter Kintsch and Robert Glaser. I became especially intrigued by the notion of exploring how research on cognition and education could be applied to and advanced in the medical domain. I wholeheartedly embraced this combination of cognitive science, education, and medicine starting in 1985, when our work at McGill University, titled "Cognitive Foundations of Medication Education," was funded by the Josiah Macy Jr. Foundation. I owe a debt of gratitude to John T. Bruer, then at Macy, who recognized that education and training decisions for medical education were too often made on an ad hoc basis rather than on the basis of science. The recognition that accompanied this grant, and the funds themselves, gave me an opportunity to explore a process-oriented approach to understanding medical cognition and expertise. It also allowed me to conduct empirical investigations that influenced curricular decisions at our medical school. In addition to the support I received from John Bruer and the Macy Foundation, I was fortunate to have enthusiastic support from Richard Cruess, McGill's Dean of Medicine at the time. He was an extremely powerful force behind my continuing interest in the topic and my belief that, through studies of medical cognition, we can gain a great deal of insight into understanding how doctors reason, and how they make decisions with incomplete information and under conditions of uncertainty. These studies also brought insight into the role that the basic biomedical sciences play in supporting clinical practice.

Over time I realized the myriad of ways in which my chosen field of cognitive science interacted and overlapped with the fields of linguistics and computer science, as well as with anthropology and philosophy. These insights were largely due to my interactions with Herbert Simon, Earl (Buzz) Hunt, David Evans, Alan Lesgold, Anders Ericsson, Henk Schmidt, Paul Feltovich, James Greeno, and Bill Clancey. Also during this period, my laboratory-based studies extended to include semi-naturalistic and naturalistic studies of clinical environments. I found that each of these study types contributed something different to the building of cognitive models of medical decision-making. I still hold this view today and I still conduct studies across this spectrum. It became apparent that, to understand medicine and the role of medical training, we first have to understand how people who practice medicine think about the problems that they solve as they go about their tasks.

My involvement with Biomedical Informatics was serendipitous, commencing in 1991 when I was asked to speak at the European Artificial Intelligence (AI) in Medicine conference in Maastricht, The Netherlands. My invited talk was intended to discuss cognitive models of medical decision-making and their implications for AI systems. I was excited about building bridges to this new field of biomedical informatics, having become convinced that my understanding of the medical field necessitates a multi-disciplinary approach. Scholars and colleagues such as Ted Shortliffe, Mario Stefanelli, Jean Raoul Sherrer, Jan Van Bemmel, and Jim Cimino greatly influenced the direction of my work towards the application of cognitive informatics in medicine. This was particularly timely, given that use of health information technology (HIT) was becoming more widely adopted in healthcare. In addition, patient care by individual practitioners was also moving in the direction of team-based care. Both of these shifts led me to reconsider my research program and set out in new directions.

Our early studies involving computing technology began to show how HIT mediates human performance. Technology does not merely augment, enhance or expedite performance, but rather it transforms the ways individuals and groups think and behave. The difference is not one of quantitative change, but is qualitative in nature. My cognitive studies also began moving towards investigations of such "real-world" phenomena. The constraints of controlled laboratory-based work tended to prevent our team from capturing the dynamics of real-world problems. This problem is particularly salient in high-velocity critical-care environments. Over the years, my studies used a multi-method approach (bench to the bedside and vice versa), which has shown synergy between laboratory-based research and cognitive studies in the "wild." An important question about how studies of individual cognition scale to teams and the real world environment where clinicians function forced me to think about the relationship between individual and team cognition.

By early 2007, coinciding with my move from Columbia University to Arizona State University, there was growing recognition that medical errors were frequent and often life-threatening. The complex nature of healthcare work was also seen as a primary barrier to the implementation of effective safety measures. Having spent long periods of time working in the clinical environment, I also came to believe that common approaches to error, which were generally based on individual accountability, could not possibly address this complexity. Strategies to eradicate error proposed by the medical community failed to appreciate that error detection and recovery are integral to the function of complex cognitive workflow. Here, I was also influenced by the work of Rene Amalberti and David Woods. Through investigations of the emergence of and recovery from error, I believed we could identify new approaches, which could capture errors and recovery processes in real time and would help identify conditions that push clinicians to the boundaries that compromise safe practices. This led me and my colleagues to submit a collaborative proposal on *Cognitive Complexity and Error in Critical Care* to the James S. McDonnell

Foundation (JSMF). The funding support that followed was once again a major breakthrough in my career and has provided me with an opportunity to explore the underlying cognitive mechanisms of error, ways to mitigate these errors in a complex healthcare setting, and ways to help bridge the underlying science to the real-world practice.

JSMF funding has been made available through their *Collaborative Complex System* program. With their support we have created a multi-site collaboratory consisting of an interdisciplinary team of cognitive scientists, clinicians, biomedical informaticians, computer scientists and psychologists. The team is geographically distributed across several research institutions – Arizona State University, the University of Texas Health Science Center at Houston, Columbia University, Emory University, Washington University in St. Louis, and the New York Academy of Medicine (NYAM). The multi-year collaboratory has evolved over the course of the research project, adapting not only to external influences such as national initiatives (e.g., the Affordable Care Act of 2009; the IOM Patient Safety Report of 2011), but also re-aligning the research agenda based on the early results obtained from each of the multiple sites.

This collaboratory brought together an eclectic group of researchers, fellows and students. In addition, the collaboratory employed an approach, which gave investigators ample freedom to pursue their research while sharing a common set of high-level goals, which converged on similar research themes. While the specific research topics varied across the different collaborating sites, the central themes remained consistent: identifying, characterizing, explaining and mitigating errors that occur in a complex critical-care environment. This was achieved by conducting research on conceptual topics that significantly overlapped across multiple sites. For example, communication, a key aspect of critical-care work activities and workflow, was addressed at three of the collaborating sites: Columbia, Emory, and NYAM. Though the projects varied in their focus, design and implementation, the outcomes were aligned to address the key challenges arising out of communication complexity. Similar innovative thinking was manifested in the research projects related to our analyses of errors and error recovery, resulting in integrated outcomes through investigations at multiple sites.

The key researchers who led the projects at the various sites include Timothy Buchman, Trevor Cohen, David R. Kaufman, Kanav Kahol, Amy Franklin, Jiajie Zhang, Thomas Kannampallil, Joanna Abraham and Lena Mamykina. Besides the critical roles of the clinicians at each site, many postdoctoral fellows, students and research associates worked closely as members of our team. Over the five-year period, my ideas were shaped by my interaction with the team, who constantly challenged me through the different perspectives that they brought to the table. The energy and insights generated through this collaborative endeavor were both gratifying and exciting.

Our research activities over this period were monitored and guided by an Advisory Board, whose members were chosen for their multidisciplinary expertise: Michael Shabot, MD, PhD (chairman), Rene Amalberti, MD PhD, Edward H. Shortliffe, MD, PhD; Alan Lesgold, PhD, William J Clancey, PhD. Each year, informed by our annual report, the Board evaluated the performance of the collaboratory during our annual Symposium. A very special thanks goes to Susan Fitzpatrick, Vice President James S. McDonnell Foundation, for her patience and her guidance over the past five years, as we maneuvered through multisite complex budget issues and researchers transferred from one institution to another.

Most of the chapters in this volume are derived from the James S. McDonnell Foundation-funded research. In the foreword to this book, the foundation's president, John T. Bruer, discusses the JSMF program background, explaining their motivation for the supported work we present in these pages. Many individuals have aided in preparing the manuscripts and copy formatting, but none more than my team from the *Center for Cognitive Studies in Medicine and Public Health* at NYAM: Lora Liharska, Corinne Brenner and Sana Khalid, all working under the careful guidance of Joanna Abraham (who also assisted with reviewing and finalizing the manuscripts). I am indebted to my co-editors and colleagues, David Kaufman and Trevor Cohen, as well as to Thomas Kannampallil, for their intellectual contributions, and for their support in dealing with the occasional inevitable challenges that occurred in the collaboratory. Finally, I wish to thank all the chapter authors. They worked diligently to generate documents from various stages of their completed or ongoing research, and then managed to meet most of my constant demands in a timely manner.

This volume does not generically represent the domain of error or complexity in medicine, but rather focuses specifically on the unifying themes of cognition, complexity, and the generation and correction of error in critical care practice. The implications of cognitive processes captured at one level of complexity in critical care provide us with an opportunity to investigate the extent to which these implications also apply to primary care practice, where the complexity level is different. The results reflect the interdisciplinary strengths of cognitive science, and offer a fresh insight into ways to investigate and mitigate errors in complex, dynamic environments such as the emergency room and the intensive care unit.

On behalf of my team, I wish to thank John T. Bruer and the James S. McDonnell Foundation for having the vision to recognize the need to invest in research that addresses the role of cognition in managing clinical errors in complex healthcare environments. We believe that this kind of work will become even more important as we introduce a new generation of technologies to support clinical practice in dynamic patient-care settings.

New York, NY, USA Vimla L. Patel

Contents

Contributors

Joanna Abraham, PhD Department of Biomedical and Health Information Sciences, College of Applied Health Sciences, University of Illinois, Chicago, IL, USA

Khalid F. Almoosa, MD, MS, FCCP University of Texas Health Science Center, Houston, TX, USA

Transplant Surgery ICU, Memorial Hermann Hospital, Texas Medical Center, Houston, TX, USA

Suchita Batwara, MBBS, MPH University of Iowa Hospitals and Clinics, Iowa City, IA, USA

Timothy G. Buchman, PhD, MD, FACS, FCCP, MCCM Emory University School of Medicine, Atlanta, GA, USA

Emory Center for Critical Care, Woodruff Health Sciences Center, Emory University, Atlanta, GA, USA

Trevor Cohen, MB ChB, PhD School of Biomedical Informatics, University of Texas Health Science Center, Houston, TX, USA

Sarah A. Collins, RN, PhD Harvard Medical School and Brigham and Women's Hospital, Boston, MA, USA

Partners Healthcare Systems, Boston, MA, USA

Amy Franklin, PhD School of Biomedical Informatics, University of Texas Health Science Center, Houston, TX, USA

National Center for Cognitive Informatics and Decision Making in Healthcare (NCCD), Houston, TX, USA

Vafa Ghaemmaghami, MD, FACS Trauma Division, Department of Surgery, Banner Good Samaritan Hospital, Phoenix, AZ, USA

University of Arizona College of Medicine, Phoenix, AZ, USA

R. Stanley Hum, MD, FRCPC Department of Pediatrics, College of Physicians and Surgeons, Columbia University, New York, NY, USA

Laura K. Jones, PhD Department of Surgery, Emory University School of Medicine, Atlanta, GA, USA

Desmond A. Jordan, MD Columbia University College of Physicians and Surgeons, New York, NY, USA

Kanav Kahol, PhD Affordable Health Technologies Division, Public Health Foundation of India, New Delhi, India

Thomas G. Kannampallil Center for Cognitive Studies in Medicine and Public Health, New York Academy of Medicine, New York, NY, USA

David R. Kaufman, PhD Department of Biomedical Informatics, Arizona State University, Scottsdale, AZ, USA

Alan Lesgold, PhD School of Education, University of Pittsburgh, Pittsburgh PA, USA

Zhe (Eric) Li, MS Drchrono Inc., Mountain View, CA, USA

Lena Mamykina, PhD Department of Biomedical Informatics, Columbia University, New York, NY, USA

Sahiti Myneni, MSE School of Biomedical Informatics, University of Texas Health Science Center, Houston, TX, USA

Bela Patel, MD, DABSM, FCCP University of Texas Health Science Center, Houston, TX, USA

Division of Critical Care Medicine, Memorial Hermann Hospital, Texas Medical Center, Houston, TX, USA

Vimla L. Patel, PhD, DSc, FRSC Center for Cognitive Studies in Medicine and Public Health, New York Academy of Medicine, New York, NY, USA

Department of Biomedical Informatics, Columbia University, New York, NY, USA

Department of Biomedical Informatics, Arizona State University, Scottsdale, AZ, USA

Velma L. Payne, PhD, MS (BMI), MBA, MS (CIS) Houston Veterans Affairs, Health Services Research and Development Center of Excellence, Houston, TX, USA

School of Biomedical Informatics, University of Texas Health Science Center, Houston, TX, USA

Elie Razzouk, MD, MS Internal Medicine, Miller School of Medicine, University of Miami, West Palm Beach, FL, USA

David J. Robinson, MD, MS, FACEP Department of Emergency Medicine, University of Texas Medical Center, Houston, TX, USA

Alisabeth L. Shine, MA Center for Cognitive Studies in Medicine and Public Health, New York Academy of Medicine, New York, NY, USA

Edward H. Shortliffe, MD, PhD, MACP College of Health Solutions, Arizona State University, Phoenix, AZ, USA

Department of Biomedical Informatics, Columbia University, New York, NY, USA

Department of Public Health, Weill Cornell Medical College, New York, NY, USA

Mithra Vankipuram, MS, PhD Analytics Lab, Hewlett-Packard (HP) Labs, Palo Alto, CA, USA

Jiajie Zhang, PhD, MS School of Biomedical Informatics, University of Texas Health Science Center, Houston, TX, USA

National Center for Cognitive Informatics and Decision Making in Healthcare (NCCD), Houston, TX, USA

Chapter 1
Complexity and Errors in Critical Care

Vimla L. Patel, David R. Kaufman, and Trevor Cohen

Introduction

This volume is unique in its focus on cognitive informatics (CI), a flourishing discipline that cuts across several academic and professional sectors. The chapters in this volume focus on motivating examples drawn from the application of methods and theories from CI to challenges pertaining to the practice of critical-care medicine. Informatics is a discipline concerned with the basic and applied science of information, the practices involved in information processing, and the engineering of information systems. Cognitive Informatics is the multidisciplinary study of cognition, information and computational sciences that investigates all facets of human computing, including design and computer-mediated intelligent action [1]. The basic scientific discipline of CI is strongly grounded in the methods and theories of cognitive science. As an applied discipline, it also draws on the methods and theories from human factors and human-computer interaction. The healthcare domain has provided significant challenges and a fertile test bed for theories from these

V.L. Patel, PhD, DSc, FRSC (✉)
Center for Cognitive Studies in Medicine and Public Health,
New York Academy of Medicine, New York, NY 10029, USA

Department of Biomedical Informatics, Columbia University,
New York, NY 10032, USA

Department of Biomedical Informatics, Arizona State University,
Scottsdale, AZ 85259, USA
e-mail: vpatel@nyam.org

D.R. Kaufman, PhD
Department of Biomedical Informatics, Arizona State University,
Scottsdale, AZ 85259, USA

T. Cohen, MB ChB, PhD
School of Biomedical Informatics, University of Texas Health Science Center,
Houston, TX 77054, USA

V.L. Patel et al. (eds.), *Cognitive Informatics in Health and Biomedicine*,
Health Informatics, DOI 10.1007/978-1-4471-5490-7_1,

disciplines. CI provides a framework for the analysis and modeling of complex human performance in technology-mediated settings and contributes to the design and development of better information systems.

Overview

The research presented in this volume is motivated by the harmful consequences of medical error, a problem that persists despite substantial efforts toward safety in the 12 years since the publication of the influential Institute of Medicine Report entitled "To Err is Human" [2]. To its credit, the IOM report was prescient in that it strongly emphasized that the majority of factors contributing to preventable adverse events are systemic and not due to the negligence of poorly performing clinicians [3]. However, observers have noted that while the report raised awareness of medical errors, little evidence exists to indicate that there have been substantial systematic improvements in healthcare safety in the time since its publication [4]. In assessment of the progress towards safety since the release of this report, Leape and his colleagues note that while the report raised awareness of medical error, "little evidence exists that systematic improvements in safety are widely available." Leape points out barriers to improved healthcare safety, amongst which "the first (such) challenge is complexity."

The work we have drawn together in this volume aims to identify new paths toward patient safety, as directed by awareness of the complexity of clinical care practice. We focus our investigations in the domain of critical care, which includes both the emergency department and the Intensive Care Unit. These environments are characterized by the need for rapid response by multidisciplinary teams with shifting priorities driven by the needs of patients that are inherently unpredictable, on account of the complex physiology underlying their disease states and the ever-present possibility of the transfer of unstable patients into the unit concerned. Thus, the interpretation of error in such environments requires an understanding of the interrelationships between the entities and artifacts that mediate patient care, and between these entities and the outside world.

In the sections that follow, we describe some characteristics of complex systems that relate to critical care environments, and their implications for the study of these environments.

Interdependencies and Open-Endedness

As is the case with complex biological and ecological systems, a healthcare environment cannot be understood by focusing exclusively on its individual components, as these components are interrelated [5]. Consequently, the framework of individual accountability that is typical of institutional, medico-legal and media responses to medical error [6], is not adequate for explaining or addressing the issue of error as it occurs in complex healthcare systems. How then, are we to approach the study and mitigation of error in such environments? Proponents of a systems-centered approach argue that significant improvements in quality and safety are most likely to be realized by attending to and correcting the misalignments among interdependent levels of care, and focusing not only on members of the clinical team and the tasks performed, but also on the broader environmental factors that constitute the workplace [3]. Negotiating the system interdependencies of care, as evidenced by continued breakdowns such as inadequate transitions of patient care, is a significant challenge faced by providers and researchers alike [3]. It should be noted that not all of the chapters in this volume are focally concerned with error; rather, they cover a range of topics such as workflow, decision-making, information seeking and communication. A systems-centered approach informs all of the research described in the volume.

The study of performance in critical settings is conducive to a systems-centered or complexity approach given the high velocity of work, the interdependence on multiple agents in the care process and the potential gravity of medical care in the setting. Systems thinking involves studying phenomena in a holistic way and understanding the causal dependencies and emergent processes among the elements that comprise the whole system [7]. Complex systems are said to have the property of emergence, in which some behaviors and patterns result from interactions among elements. The systems are also characterized by feedback loops, both positive ones which serve to amplify an effect and negative ones which serve to dampen it. The boundaries of a system can be construed as open-ended and observer-defined. For example, an intensive care unit can be studied in terms of teamwork activity that focuses on the care of a single patient, workflow in the entire unit at a given point in time, and communication that stretches beyond the boundary of the unit. One may also choose to situate the unit within the sociocultural or economic boundaries of the hospital, the local community or even within the greater healthcare system. Of course, different research questions necessitate different units of analysis.

Methodological Imperatives for Taming Complexity

Given the degree of interrelatedness of a complex entity, how can we render it a proper subject of inquiry? How can we make the study of a given a phenomenon, such as handoff communication, tractable? One such strategy is functional decomposition in which complex systems can be decomposed into smaller functional components and the relations between them [8]. The objective is to cut a system at its seams, thus rendering the problem tractable without doing violence to the system as a whole. Another strategy is based on the figure-ground metaphor. One may choose to shine a bright light on the foreground, illuminating a phenomenon of interest, and a dimmer light on the background. In this regard, one never loses sight of the context and one may choose to bring different facets of context to the foreground in sharp view, as their relevance becomes apparent. It is also possible to invert the image where the foreground recedes and the background surfaces as the focal point for scrutiny. A case in point is the study of handoff as a verbal exchange between a clinician finishing a shift and one just beginning a shift. One may also situate the handoff event within the stream of clinical communication including other handoffs and patient rounds. It can also be connected to the ongoing activity/workflow involved in taking care of the patient who is the subject of the handoff communication. Both the functional decomposition (FD) and the figure-ground (FG) research strategy are employed in the research described in this volume. The FD strategy is particularly useful for in-vitro or laboratory-based studies, whereas the FG study supports naturalistic or ethnographic field studies.

The authors of the chapters in this volume provide a range of methodological alternatives, each of which provides new insight into important but sparsely investigated issues such as the nature of error recovery and communication in critical care, the ways in which interactions between individuals direct the course of clinical work, and the applicability of interventions based on normative models of clinical decisions such as guidelines, which are often constructed without consideration for the environment in which they are to be implemented.

One line of research focuses on the study of error recovery, motivated by work in other error-critical domains, which suggests that development of error tolerance is a more practical safety goal than the outright of error [9]. The framework of individual accountability, predominant within the medical community, is further reinforced by the litigious nature of healthcare practice in the United States. Implicit in this framework is the assumption that human error in medicine *should not* occur. This assumption is flawed, as complex work environments are not conducive to the definition of normative models of optimal task performance. Furthermore, it is incompatible with current thinking on the role of error as a component of "learning the ropes" in such environments [10]. This suggests the need to shift focus from the elimination of error toward the mechanisms through which the potentially harmful consequences of error are eliminated. Error is viewed as something that cannot be eliminated, but is usually negotiated in complex environment [11]. However, the mechanisms of error detection and recovery in complex clinical settings are currently poorly understood. This provides further motivation for this line of research, which evaluates the ability of clinicians to recover from errors using a range of complementary methodologies, from laboratory-based studies involving case scenarios with embedded errors to naturalistic studies of spontaneous error recovery as it occurs during clinical rounds. Our studies in this area suggest that focused individual attention [12], the availability of expertise [11] and team interaction [13–16] all play important roles. However, the distribution of attention, expertise and team members in a complex healthcare system is inherently unpredictable, as this distribution is an emergent property of a workflow that is directed by circumstance and patient needs [8, 17].

Therefore, a deeper understanding of workflow in such environments is desirable. However, this presents its own methodological challenges. Methodologies evaluated as a means to characterize this workflow include human-intensive observation supplemented by technological tools to mediate rapid and consistent annotation of workflow activities [17]. However, human observers are largely constrained to a single stream of attention, as well as to a specific spatiotemporal location, and as such are limited in their ability to capture the interactions between multiple team members that underlie the complexity of clinical workflow. Automated approaches in which the movements of multiple team members are monitored using Radio Frequency Identification (RFID) tags are evaluated, and shown to contribute new insights into clinical workflow [8, 18], including the characterization of team aggregation and dissemination as emergent properties of the system as a whole.

The non-linear nature of the flow of activity demonstrated in these studies raises issues for the design of interventions intended to enhance patient safety in clinical settings. Interventions based on a static, normative model of clinical decision making such as practice guidelines and checklists have been successful in addressing medical error in certain circumstances [19]. However, outcome measures aside, little is known about the ways in which such interventions are implemented in the context of an existing sociotechnical ecosystem. The results discussed in this volume show considerable variability in the ways in which these interventions are implemented in practice [20, 21], suggesting opportunities for customization and training to further improve outcomes.

Research in workflow has increasingly focused on particular communication events, which are instrumental in coordinating clinical practice. In recent years, handoff has been the subject of many investigations [22]. However, researchers have often focused on understanding handoff as a discrete communication event, independent of other activities in the clinical workflow. Abraham and colleagues argue that handoff must be examined within the overall context of the clinician workflow, considering activities prior to, during, and after information transfer [23]. The developed methodological framework situates handoff within a broader temporal stream of clinical workflow activity. The clinician-centered approach is predicated on capturing the contextual factors that impact the continuity of care across multiple clinicians providing care for a patient. The focus is on continuity of care as realized in a "day in the life" approach.

The clinician-centered approach employs a series of methods with a particular focus on shadowing clinicians. The objective is to develop a "more accurate and nuanced representation of the overall handoff process with respect to a temporal sequence of the clinician's information management and transfer activities as they relate to patient care events" ([23] p.242). This approach, which characterizes the interdependencies between the various workflow components, can yield insights into a range of contextual factors that mediate quality of care. It also serves to surface and identify the source of breakdowns in communications and clinical errors.

In the sections that follow, we provide an overview of the research described in this volume, grouped in accordance with four themes that emerged during the course of this research. The first of these relates to the cognitive processes that underlie decision-making in critical care. Motivated by the inadequacy of normative models to account for the relationship between variability of clinical practice and patient safety, these studies focus on the recovery from error in critical care, and the cognitive and environmental factors that drive decision making in this context. The second and third themes relate to communication and clinical workflow, and the ways in which the unpredictable nature of these interactions may impact patient safety. The final theme provides overall lessons learned from clinical, education and informatics perspectives.

Error Recovery, Standardization and Decision-Making

It has been argued that the tendency to strive toward perfection is inherent to the culture of medical practice, and that this tendency has made it difficult for practitioners to acknowledge, and hence learn from, errors [6]. Arguably, this tendency has also impacted the efforts taken toward improving patient safety, many of which have proposed error reduction, or even error elimination, as goals. While these are laudable goals, the implied "quest for zero defect" has been largely abandoned by researchers in other safety critical domains [24]. This shift in perspective, and its implications for the study of error, are discussed in Chap. 2 of this volume. This chapter addresses the theoretical rationale for the set of error chapters to follow, and concerns contemporary approaches to error that are able to address the complex nature of critical care work. The complex nature of healthcare work has been proposed as a primary barrier to the implementation of effective safety measures. Approaches to error based on individual accountability cannot address this complexity. Patel and Cohen introduced the phrase 'error in evolution' that denotes the progression of a series of small mistakes towards a cumulative adverse event. This progression is not inevitable: erroneous decisions undergo a selection process based on their anticipated consequences [15]. The authors of this chapter argue that focusing on this process of recovery, rather than producing situation-specific 'quick fixes,' is more likely to reveal generalizable mechanisms of error recovery that can support widely applicable solutions.

The authors of Chaps. 3, 4, 5, and 6 develop new experimental paradigms for investigating the nature of error recovery in the critical care context. While two of the three experimental approaches concern the presentation of cases with embedded errors to clinicians, they all differ from one another in important ways.

Chapter 3 documents studies of error-recovery by individuals in a laboratory setting, using written case scenarios, as described earlier. A striking finding from this research is that error detection by both domain experts and trainees under these conditions, was on the whole, alarmingly poor. While experts did show some advantage in dealing with more complex errors, it was possible that the use of paper-based cases in a laboratory environment may be sufficiently removed from the real world practice environment that cognitive cues and other factors promoting error recovery in practice may be lost.

The research described in Chap. 4 investigates another aspect of this problem, the role of team interaction in error recovery. Clinical rounds have previously been identified as high-yield activities for error detection and recovery [13, 14], as they provide a focal point of information exchange and the opportunity to address errors made by other clinicians. In order to investigate the effects of these aspects of the clinical environment on error recovery, case scenarios with embedded errors were presented in the context of real-world clinical rounds, while recording the interactions between team members that occurred in response to these scenarios. The overall trend indicates that teams of physicians are better able to detect errors than individuals. More interaction between team members was associated with more effective error recovery, and detailed qualitative analysis of these interactions revealed instances in which the detection of and recovery from an embedded error was accomplished collaboratively. This indicates that interaction promotes recovery; an unexpected finding of this research was that new errors were introduced during the process of interaction. Recovery from these errors did not always occur, suggesting that in a complex environments when trainees are present, it is essential that adequate supervision occur, such that the potential for learning is realized, and the potential for adverse events averted.

Extensions of this study were performed in naturalistic settings (Chap. 5) where the data from three morning rounds were audio-recorded in real time in a medical ICU environment covering 35 patient beds. Using methods of conversational analysis, this study showed that teams working at the bedside optimized performance with little room for generating and explicating any mistakes. There appears to be an inherent check within the team (with time pressure) in a naturalistic environment to correct any mistakes quickly. This ability to correct errors also supports the results from our previous naturalistic study [13]. These results and their relationship to competent performance and learning are discussed in this chapter.

Chapter 6 documents an alternative approach to addressing the gap between the laboratory setting and real-world clinical rounds. To better approximate clinical case presentation in remove a controlled experiment, Razzouk and colleagues generated simulated clinical rounds in the context of a computer-based three-dimensional immersive virtual world created with the OpenSimulator development platform. In addition, knowledge-based questions related to each embedded error were added, to distinguish between failure to detect errors on account of ignorance and failure on account of some other cause. Finally, the notion of priming was introduced, which in this context refers to alerting participants to the presence of errors in the case. This suggests the possibility of the development of training modules with this task in mind, an idea that has been proposed in the context of aviation [25]. To this end, the chapter also discusses the development and evaluation of an online tool that adapts the cases used in our experiments for the purpose of training physicians to detect and recover from error.

In summary, the results of our studies on error recovery suggest that both directed attention and team interaction contribute to recovering from errors. However, in a complex work environment the distribution of attention and team members is unpredictable. In Chap. 7, Franklin and colleagues aim to quantify this unpredictability by characterizing the forces that drive clinicians in an Emergency Department (ED) toward a particular course of action. An important finding of this research is that choices made in the ED are more often driven by situations in the environment, rather than by conscious selection. That is to say, rather than being guided by protocol, situational factors such as spatial proximity to a particular patient or colleague direct the course of action in the ED in many cases. This degree of non-deterministic behavior strengthens the analogy between critical care units and complex systems. In general, it also raises issues relevant to intervention in such settings, as the non-linear nature of this workflow may be poorly suited to standardized treatment protocols.

The extent to which standardized protocols, such as treatment guidelines, are effective in a complex workspace is a recurring theme in this volume. In Chap. 8, Vankipuram and colleagues investigate this issue by observing and characterizing deviations from standard protocol in the context of a trauma unit. While some of these deviations represented errors, it was observed that in many cases they represent dynamic adjustments to the operating conditions within the unit, made in order to enhance efficiency by being responsive to the surroundings. Such adjustments, termed "innovations," were found to account for a substantial proportion of deviations by experts; deviations made by trainees, on the other hand, generally represented errors. Guidelines may serve to provide assistance for trainees, but the improvisations observed during this study suggest that excessive standardization may impede the efficiency of expert practice [20].

Myneni and colleagues (Chap. 9) similarly address the utility and limitations of standardization with respect to weaning patients off of ventilators in an ICU setting. Standardizing a care process through the use of health information technologies is seen as a viable way to reduce medical errors by diminishing unnecessary variation in the care delivery. However, the dynamic nature of critical care environments demands context-specific and complexity-inclusive assessment of these standardization strategies for optimal results. The authors describe three studies that focus on the safety assessment of a Computerized Weaning Protocol (CWP), which has been used to standardize the weaning process of mechanically ventilated critically ill patients. The studies employed a range of methods and identified several risk factors that were either inherent to the particular protocol or externalized in the environment. This chapter provides an overview of techniques that can be used for fine-tuning and optimizing HIT-based standardization interventions such as the weaning protocol, thus improving patient safety.

The majority of studies described in this volume employ a naturalistic decision making (NDM) approach. However, Payne and Patel (Chap. 10) develop a hybrid approach that embraces the study of heuristics and biases, more typical of the classical decision-making approach with ethnographic methods more exemplary of NDM. Critical care settings are complex environments that are stressful, time-sensitive and interruption-laden, where clinicians, influenced by factors such as extended work hours and sleep-deprivation, make life-critical decisions. In such settings, decision-making requires the use of cognitive heuristics in order to sustain the required pace. The authors demonstrate a method for eliciting heuristics and biases in critical care settings and use the illustrative study to develop a framework. The authors then demonstrate that the framework can be used to facilitate identification of specific actions associated with heuristics and biases that result in better