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Theories, Models and Frameworks for Diagnosing Technology-Induced Error

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Abstract

Information technology has the potential to greatly streamline healthcare and reduce the chance of human error. However, there is a growing literature indicating that if systems are not designed adequately they may actually increase the possibility of error in the complex interaction between clinician and machine in healthcare (i.e. they may lead to technology-induced errors). In other domains the study of error has been guided by a variety of theories, models and frameworks for understanding human error. In this paper we argue for the need to consider and extend this work to the study of technology-induced error in healthcare. Insights from the software engineering, human factors and organizational behaviour literature will be described, including a set of models and frameworks that we have been using to guide our work in detecting and preventing technology-induced error in healthcare.

Keywords:

Technology-induced error, Evaluation, Theory, Models, Frameworks, Software engineering, Organizational behaviour, Human factors, Socio-technical theory

Introduction

The evaluation of health informatics applications is becoming an increasingly more important activity as the number of health information systems (HISs) that are being implemented in healthcare settings continues to grow. Historically, summative evaluation methods were used to determine if a HIS led to improved clinical outcomes, reductions in costs, or reductions in medical error rates (thereby improving patient safety) [1]. However, in recent years, researchers have also found that formative evaluation is essential to identifying other issues associated with a technology's use (such as socio-technical issues and technology-induced errors) [2,3,5]. No where is this more apparent than in the use of evaluation to study technology-induced errors. In the literature technology-induced errors have been defined as those sources of error that "arise from: (a) the design and development of technology, (b) the implementation and customization of a technology, and (c) the interactions between the operation of the new technology and the new work processes that arise from a technology's use" [4, p.154]. Unintended consequences are unexpected results of use of technology that "lack a purposeful action or causation" [6, p. 415]. Technology-induced errors are one type of unintended consequence arising from the use of HISs by clinicians [3,4,6]. Researchers have used many evaluation methods and approaches to identify the presence of technology-induced errors [2,3,6]. The evaluation methods used in the study of technology-induced errors range across a continuum of approaches from purely qualitative to mixed method and then exclusively quantitative approaches [7]. These methods have been used to evaluate technology-induced errors arising from the use of HIS software and devices at varying points in the software development lifecycle through to HIS implementation in healthcare organizations (including the customization of software applications, the selection of devices and the long-term maintenance of applications and devices in clinical settings) [7]. Although many evaluation methodologies have been used to identify sources of technology-induced error such as interface features and functions [2], database content [2,6] and workflows emerging from interactions between software, devices and organizational settings [6,8], these evaluation methodologies have only been able to identify specific types of errors at specific time points: (a) in software development [2], (b) prior to organizational implementation of software and devices [8], and (c) after organizational implementation of software and devices [6]. For example, some researchers have been able to identify potential sources of technology-induced errors during the software development lifecycle [2]. Other researchers have identified sources of unintended consequences after a system/device has been implemented in a real-world setting and the system/device is being used at point of care [see 6]. It is interesting and worthy to note that some of the same unintended consequences or technology-induced errors that have been identified by researchers studying applications and devices both before and after a system/device has been implemented in an organizational setting [3,6].

Therefore, there is a need to develop a more holistic understanding of technology-induced errors and how they propagate throughout a system [4]. This holistic understanding needs to take the form of models, frameworks or theories that span the entire software development process through to organizational implementation and maintenance of software and devices. Such theoretical work will help us to understand where errors come and how those errors are propagated throughout the HIS development, implementation and maintenance process [4]. Therefore, there is a need for researchers to describe the differing types of technology-induced errors and their unintended consequences (arising from technology use) [4,6]. There is also a need to better understand the implications of software errors that arise during software design, development and implementation upon future clinician work at point of care (as has been done in other industries) [2,4,8].

Some researchers have suggested that error models can be imported from other industries (i.e. aviation, banking, nuclear power) [2,6,9]. Other researchers have indicated healthcare has unique features that do not allow for theories and models developed in other industries to be easily applied in healthcare settings [10,11]. For example, researchers have found that healthcare work is variable, dynamic, complex, emergent, involves a high degree of ambiguity, is inter-professional in nature, is highly professionalized, requires a high degree of coordination and is not easily deferred (unlike work undertaken in other industries such as banking, mining) [10,11]. Furthermore, some researchers have found [10], healthcare places additional pressures upon its workers (e.g. physicians and nurses) to provide continuity of care. As a result, models of error cannot be easily imported into healthcare due to the unique features of the setting and in some cases these models require modification or extension. This is consistent with other industries where theories, models and frameworks from other domain areas are imported and then modified in response to empirical testing for their applicability in another domain (e.g. theory from sociology and psychology has been applied, modified and extended through empirical testing in the management and aviation industries) [see 10, 13].

Therefore, there is a need to empirically validate models of error from other industries for their applicability to healthcare and the field of health/biomedical informatics. These models need to be empirically validated, falsified, extended and customized for healthcare and in some cases researchers need to develop new models for describing technology-induced error that are specific to the healthcare industry as has been done in other industries [10,12,13]. Such work is necessary in order to diagnose potential errors involving technology before they occur in real-world settings. Many of these frameworks, models or theories specific to health/biomedical informatics that have been published are still in their infancy from a theoretical, conceptual and empirical perspective. Research is needed to empirically test these models and more research is needed to determine if these models can predict error. Such developed and empirically tested models will allow health informaticians to engage in "targeted" testing of software, hardware and interactions between applications/devices that may lead to technology-induced errors in order to eliminate them before the application/device is introduced into a real-world environment. The authors of this paper intend to take the first step in this process by outlining the frameworks, theories and models that are currently being used in health/biomedical informatics that conceptualize technology-induced errors.

Health informaticians need to begin the process of developing frameworks, models and theories. Frameworks, models and theories once developed and tested could be used to prevent and predict future sources of technology-induced error (from software development through to the implementation and maintenance of systems). The authors of this paper conducted a search of Medline using the key phrases "technology induced error and framework", "technology induced error and model", "technology induced error and theory", "technology-induced error and framework", "technology-induced error and model", "technology-induced error and theory", "unintended consequences and framework", "unintended consequences and model", unintended consequences and theory", "e-iatrogenesis and framework", "e-iatrogenesis and model", "e-iatrogenesis and theory". Two authors reviewed each of the titles of the published articles and proceedings that were returned on each of the searches. If the title or abstract of the article or proceeding referred to a framework or model or theory and technology-induced error or unintended consequences or e-iatrogenesis then the full article was reviewed by two authors to determine if a framework, model or theory was indeed described (i.e. 191 citations were returned 6 were identified by the authors using the above mentioned criteria and the articles were downloaded and reviewed). All articles in Medline from its inception to the end of 2009 were searched using the above strategy. We also included models of technology-induced error that were published in health informatics texts up to and including 2009 to inform the work. The frameworks, models and theories from the health/biomedical informatics literatures that were identified and will be discussed in this paper. The frameworks, models and theories were grouped by the authors into four paradigms: software engineering, human factors, organizational behaviour, and multi-theory model and framework approaches.

Software Engineering Approaches

Software engineering has a long and established tradition of research documenting testing methodologies that can be used to empirically evaluate software applications, devices and interactions between applications/devices as they contribute to worker error rates. More specifically, the software engineering literature identifies that inadequate programming, requirements specification, design, customization, and beta testing can lead to software errors once an application is implemented in an organization. Many publications and texts provide details about the differing types of general software testing methodologies - arguing for the need to conduct testing early in the software development process in order to reduce costs associated with addressing software errors after an application has been implemented (i.e. the later an error is discovered in the software development and implementation process, the higher the costs associated with correcting the error(s) that arise from the software once it has been implemented). It must be noted that a strength of the models and frameworks from this literature are the empirical research supporting and the breadth and the applicability of these models to many industries where software/devices are being used to improve the effectiveness and efficiency of work processes [4].

The strength of the software engineering literature is also its weakness. Much of the literature is based on research done in industries where transactions are simplistic in nature (as compared to healthcare) and there are few urgent or life threatening decisions that have implications for individuals (i.e. patients). Additionally, requirements specification approaches are tacit in nature and users' beliefs about their work practices are not easily elicited during the requirements specification process. For example, findings from the empirical literature indicate that [18, 20]: a) a work process does not always occur in the way that users think it occurs, b) the way users carry out activities may vary by user, and c) rules and procedures that involve an application/device may be "broken" by users or not followed.

Lastly, unlike other industries, health/biomedical informatics has been slower in its evolution and application to real-world settings. There are many reasons for this. In some cases there is an inability for healthcare to obtain the necessary funding to support software development and the complexities of designing and developing applications for the healthcare system. In addition to this, testing approaches from the software engineering literature have limitations as they do not take into account the challenges of providing services in urgent care healthcare settings (i.e. hospitals) where the stresses that an application/device must effectively respond to are significant -especially when a patient's healthcare is complex, urgent and requires intervention by multiple and differing health professionals. It is because of these limitations that health/biomedical informatics researchers have identified the need to develop frameworks, models and theories that attend to the complexities of patients and the organizations (i.e. hospitals, home care agencies and physician offices) that attend to them.

Human Factors Approaches

A variety of models of human-computer interaction can be applied to the problem of reducing technology-induced errors in healthcare. Eason [13] in an influential paper provides a framework where human-computer interaction can be considered in terms of levels, ranging from Level 1 interactions between individual users, to Level 2 interactions involving use of computer systems to carry out work tasks, to Level 3 interactions at the more complex layer of social and organizational interaction. This framework has proven useful in providing a rational and efficient approach to identifying where technology-induced errors may arise [15]. For example, in conducting analyses of systems such as medication order entry, at Level 1 certain interface features may induce users to make data entry errors (e.g. unclear or inconsistent user interface operations). Moving up to Level 2, the use of a system may be problematic once it is implemented in a real-world healthcare setting, where the user interaction (e.g. in entering a medication) may be interrupted during medication administration tasks involving patients. Finally, at Level 3 the system may introduce problems and errors if it interferes with the complex communication among healthcare workers.

A second influential error model referred to in the literature has been Reason's model of human error. Reason's [9,14] approach distinguishes between a "sharp end" and a "blunt end" where error may arise in complex human-computer interaction. It is at the sharp end that errors are made by humans, however, the origins of such errors may be at the blunt end of the continuum, that is, at the end involving the complex organizational processes, policies and environments that may eventually lead to error at the sharp end. In a paper by Keay and Kushniruk [15], Eason's framework [13] and Reason's model [9,14] of error were integrated with Eason's Level 1 interactions corresponding to Reason's sharp end, and Eason's Level 3 interactions corresponding to Reason's blunt end. In more recent work, Borycki et al. [16] have extended and elaborated Reason's model to include consideration of sources of error specific to healthcare informatics and technology-induced error that blends work in human-computer interaction and human error with theory from the organizational behaviour literature (and which is described in the next section).

Organizational Behaviour Approaches

Health/biomedical informatics researchers have suggested that there is a need to blend in works from the organizational literature to address the limitations of the software engineering and human factors literatures in developing theories, models and frameworks that can act as an aid to the study of technology-induced errors in healthcare organizations. Borycki and colleagues [16] have proposed a framework that can be used to diagnose technology-induced errors that draws on the organizational behaviour literature. The framework borrows from Reason's work in the human factors literature [9] and Orlinkowski's [17] work at the intersection of the organizational behavior and the information systems literatures. In this framework the researchers recognize that HIS are developed against a policy and regulatory backdrop that influences organizational functioning (e.g. hospital and vendor), vendor systems design and development of HIS and the procuring organization's (e.g. hospitals) selection and day to day operation of a system/device. The framework identifies that systems are designed using a model organization. Software requirements approaches and modeling techniques are used to gather data and describe organizational processes. These approaches and modeling techniques serve as the foundation for HIS design and development. In the organizational behavior literature, it is recognized that organizations are imperfect and that all model organizations do not have ideal processes [17], these processes may be error prone [9] and processes can be undertaken in varying differing ways [18].

Vendors who develop software based on the work processes found in a model organization [4,17] may inadvertently design and develop HISs that integrate errors into their software applications. In addition to this, vendors in the process of programming, designing and developing a HIS may introduce new types of errors (i.e. programming errors, errors arising from inadequate requirements specification and design). The model also recognizes that the organizational acts of procuring, customizing, implementing and maintaining such systems may introduce new opportunities for errors: those arising from a policy and regulatory backdrop, the model organization, the vendor, and the adopting organization's own customization and implementation processes. Lastly, when a new HIS is introduced during an implementation, users do not use the technology as vendors and healthcare organizations intended the technology to be used [16,17]. Each of these layers – those at the policy and regulatory level, the model organization, the vendor and the adopting organization each have an opportunity to introduce new types of technology-induced errors and when the "holes" line up in the defensive layers of the complete system the "trajectory of accident opportunity" occurs) [9]. Borycki et al.'s [16] extension to health informatics recognizes that the causes of error can be located on the blunt end with the policy and regulatory environment and the model organization on which a design is developed to the sharp end where healthcare workers use the HIS at point of care in the procuring or adopting organization.

Another model that draws on the organizational behaviour literature is Leavitt's diamond model from the 1970's [19]. Leavitt's model may allow one to track the trajectory of accident opportunities, and inversely, it may also be useful at exploring the events of an accident in order to trace out the root cause of errors (i.e. the blunt end). Leavitt's model for organizational change is based on the principle that any change in one of the four elements, 'task', 'actors', 'structure', and 'technology' (in a later extension of the model also a fifth element, 'organizational environment') will propagate to the other elements of the organization in a domino reaction until a new, steady state is reached. Such changes may lead to new events taking place, new procedures, or unforeseen problems with a new technology, and so on. That is, compensating reactions will result as a consequence of introducing a change agent (also implying that changes will be visible in places where the change was originally introduced to the organization). In Brender [20], Leavitt's model for organizational change is integrated with Mumford's socio-technical work (participatory design, also from the 1970'ies) as a methodology for testing objectives fulfilment and hence for revealing the complementary reasons for why an organization does not achieve what it had anticipated from the systems development/change effort, while enabling root cause analysis of identified problems.

Diffusion theories from varying literatures have been a source of inspiration for many researchers from many domain areas (e.g. management, health/biomedical informatics) [6, 22-24]. Roger's text entitled "Diffusion of Innovations" [22] has provided insights to some researchers as to the varying factors that affect a technology's diffusion [6,22]. For example, Roger's [22] provides an overview of how communication channels influence an innovation, identifies the main attributes of a technology that influence its diffusion through a social system and identifies the intended and unintended consequences associated with the use of a new technology. Ash et al. [6] extend work documented in Roger's text [22] to healthcare. Ash and colleagues document the intended and unintended consequences associated with using a physician order entry system and develop a thematic hierarchical network model for the consequences of using physician order entry. The researchers use ethnographic observational and interview data and derive their model from the qualitative findings of their study [6].

Multi Theory, Model and Framework

Lastly, an Interactive Sociotechnical Analysis Framework [21] has been developed by researchers in health/biomedical informatics. Harrison and colleagues [21] draw upon multiple theories, models and frameworks to develop their model. Their work has its origins in the socio-technical, ergonomic, social constructivist and the technology-in-practice literatures which have long empirical tradition. The framework identifies there are relationships between health information technologies, clinicians, workflows and organizational environments. The developers of the framework suggest that new health information technologies (HIT) change existing social systems, interact with existing technical and physical infrastructures, the social system mediates HIT use, HIT use changes the social system and these interactions between the HIT and social system lead to technology redesign. The authors cite several empirical works to support their development of the framework.

Theories, Models and Frameworks: Diagnosing Technology-induced Errors

In our work in predicting and preventing technology-induced error in healthcare we have blended the use of many of the approaches described above [2,4,7,8]. For example, we have conducted usability and laboratory-based simulation studies explicitly targeted at Eason's level 1 interactions, involving think-aloud studies of users interacting with health information systems in isolation [2]. In our work we have been extending frameworks and models by applying simulation methods (involving video observation of health professionals interacting with systems to carry out simulated and real work tasks) corresponding to Eason's Level 2 interactions [8]. Likewise, Reason's model of error has led us to conduct analyses targeted at both the sharp and blunt ends of the error continuum. Using one strategy we have started with the occurrence of an error (at the sharp end) and then traced the error back to possible blunt end causes. In addition, we have also conducted preventative analyses of error, by beginning at the blunt end of organizational factors (and using the framework outlined by Borycki et al. [16] that extends Reason's work to healthcare informatics) and then progressively moving to the sharp end to assess the potential impact of organizational and policy choices on error at the human end.

Discussion

In this paper we have described a number of approaches to the study of human error that can be applied and extended to the prediction and prevention of technology-induced error in healthcare. We must ensure that the information systems we deploy in healthcare do not inadvertently add new forms of error. However, due to the complexity of healthcare processes and work activities, the potential for information technology to cause technology-induced error is a growing concern. In this paper we have argued that an eclectic approach to considering technology-induced error that draws on theories, models and frameworks from a range of disciplines is needed. This will lead to a more principled and effective deployment of applications/devices.

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