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Title: An Analytical Methodology to Support the Identification and Remediation of Potential Human Fallibilities in Complex Human-Machine Systems

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This research proposes a Human Fallibility Identification and Remediation Methodology (HFIRM) that supports the systematic identification and remediation of potential human errors. The objective of this research was to develop and test a prototype framework that supports the practical application of human factors knowledge to the analysis and design of complex systems. This was accomplished through the development of a methodology that guides users through a systemic fallibility analysis that draws from a database of human performance knowledge. The results of the preliminary usability study suggest that participants perceived HFIRM positively in terms of both its usability and efficacy, supporting the face validity of the framework. This methodology extends existing research in the domain of human error analysis and incorporates human factors principles in order to develop a novel human performance analysis methodology.

An Analytical Methodology to Support the Identification and Remediation of Potential Human Fallibilities in Complex Human-Machine Systems

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Leslie Braitsch Thompson, Author

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Introduction

The discipline of human factors is dedicated to the study of human capabilities and limitations, with the objective of designing more efficient, effective, and safe systems.   The research conducted in this field has yielded valuable knowledge regarding how humans process information and make decisions and execute actions. The result is a significant body of knowledge regarding how and why humans make errors during the performance of goal-oriented tasks.

The study of human performance has identified numerous specific ways in which the cognitive and physical abilities of humans are limited. Despite individual differences in capability, all humans share the same basic cognitive architecture. Accordingly, individuals make similar kinds of mistakes while processing stimuli and executing intended actions. The fundamental limitations of the human mind and body, and the strategies that we employ to cope with those limitations, result in certain error tendencies. These human fallibilities[1] are the precursors to the human errors that negatively influence goal-oriented performance.

Every system in which humans play a role is susceptible to performance decrements due to human error. However, the performance of every system is not threatened by every human error tendency. Human fallibilities are more likely to be manifested as human error under certain circumstances. To the extent that we understand these performance-shaping factors, we can design tasks and processes that do not place operators in situations that they are cognitively or physically ill-equipped to successfully negotiate. Reducing human error requires identifying and avoiding situations where human fallibilities are likely to manifest themselves.

Designing systems that accommodate the numerous and sometimes conflicting informational processing needs of humans requires a comprehensive

[1] Fallibility: “The state or fact of being fallible; liability to err or to mislead (in mod. usage limited to the former); an instance of the same.” (Oxford University Press (1989), Oxford English Dictionary Online, Second Edition (fallibility). Retrieved April 5, 2008, from http://0-dictionary.oed.com.oasis.oregonstate.edu/entrance.dtl, Second Edition, 1989).

understanding of the variables that affect human performance. Empirical studies of the conditions under which operators make certain types of errors have contributed significantly to our understanding of human fallibilities. The variables that shape human performance include characteristics of the individual performing the task, the environment in which the task is being performed, and the task itself. Effective human-centered design requires thorough consideration of each of these factors, both individually and as they relate to one another.

Designing human-machine systems to accommodate human limitations may reduce the probability of human error. However, because human behavior cannot be perfectly predicted, human error cannot be totally eliminated. As a result, even systems that are designed to minimize human error are still susceptible to it. The implementation of appropriate system defenses can prevent human error from resulting in undesirable system outcomes. Countermeasures may prevent errors from cascading unnoticed through systems and may mitigate the negative effects of errors. By utilizing human factors principles and appropriate system defenses, designers can develop robust, high-performing, error-tolerant systems.

Human factors engineering is a data-rich field, and the sheer volume of existing knowledge regarding human performance makes its systematic application challenging. Additionally, high-risk systems are often extremely complex, complicating their examination. Experts have addressed the challenge of applying human factors knowledge to analyses of complex high-risk systems by developing a variety of models for reducing both the probability and the adverse effects of human error. Although most of these models attempt to classify human errors in order to identify and remedy system vulnerabilities to human error, the models range in their specific approach, their sophistication, and their utilization of human factors principles.

This thesis presents a model for the rigorous knowledge-driven analysis of complex human-machine systems which is applicable during both the design phase and after implementation of the system. The tool guides human factors experts and system experts through a series of prompts for specific information regarding the target task and information regarding the human fallibilities that may be manifested during the task. For each potential human fallibility, analysts are provided with human factors guidelines that are relevant to either understanding how the potential fallibility may affect performance or to preventing the fallibility from adversely affecting system performance. The methodology draws human factors information from a database which describes relationships between key elements of human performance. This information supports the analysis of the target system by promoting the consistent and effective utilization of human performance knowledge.

Statement of Need

Extant error analysis frameworks approach the issues of human error from a variety of perspectives, however each model exhibits at least one of several fundamental shortcomings: they do not address the underlying causes of human error, their domain of interest is limited to specific industries or environments, they focus primarily on retrospective accident analysis and reporting, they lack rigor and are therefore highly susceptible to analyst error, or they do not draw on a strong foundation of human factors knowledge.

There is a need for a generalizable model that utilizes human factors knowledge to support cause-oriented, prospective, rigorous, information-driven analyses of human error within complex human systems.

Statement of Objectives

The objective of this research was to develop and test a prototype tool that supports the practical application of human factors knowledge to the analysis and design of complex systems.

Specifically, the objectives of this research are to:

- Systematically define an analysis procedure that facilitates the prospective identification of potential errors.
- Support the remediation of potential errors by providing analysts with the necessary human factors information to design focused interventions.

These objectives were accomplished through the design of a framework that consists of a systemic fallibility analysis that draws from a database of human performance knowledge. The prototype methodology supports the identification of situations that have the potential to result in human errors. The fallibility analysis consists of a defined action sequence for performing a principled examination of the target system. The analysis identifies tasks during which system variables make certain human fallibilities possible, and provides human factors guidelines relevant to preventing those fallibilities from precipitating negative system outcomes.

The methodology draws on a human performance database that organizes and synthesizes a limited amount of existing human performance information. Definitions were created for relationships between system variables (characteristics of individuals, tasks, and environments) which may represent human error precursors and, in the absence of defensive design features, precipitate human error.

This thesis provides a foundation for further research by designing a fallibility analysis methodology, creating a prototype human fallibility database to support the analysis, and developing and populating the database to the point where it can be applied to a real-world system.

Statement of Scope

The goal of this thesis was to provide a prototype methodology and direction for future research. To support this objective, resources were primarily dedicated to the creation of the conceptual framework and the prototype database. The database was developed to a level where it can adequately support the application of the analysis tool to a real-world system. A preliminary usability study was conducted in order to guide future development of the methodology.

Opportunities for future research include refining the database entity-relationship structure, populating the database with a broader range of information, and increasing the functional sophistication, flexibility, and usability of the software interface. These development opportunities are not included in the scope of this research, but detailed recommendations for development are presented in the

Future Research and Development section of the Conclusions and Future Research chapter.

Thesis Overview

This document provides an introduction to existing human error analysis models, a description of the objectives and development of this thesis, an overview and evaluation of the resulting analysis framework, and opportunities for future development. The *Literature Review* chapter provides readers with a brief comparative analysis of the key concepts and research that contributed to the theoretical foundation of this thesis. Human factors principles, information management techniques, modeling approaches, and existing methodologies for analyzing and categorizing human error are described. The *Development* chapter presents the objectives and goals of the methodology and its supporting database, and outlines the method used to develop each component of the analysis framework. Additionally, the *Development* chapter describes and demonstrates the resulting Human Fallibility Identification and Remediation Methodology (HFIRM) prototype. The *Usability Study* chapter presents the objectives of the study, the design and instruments, and the results of the study. The *Discussion* chapter identifies the strengths and weaknesses of the HFIRM prototype by evaluating the extent to which the goals were achieved and by considering the prototype analysis in the context of the critical dimensions of human performance models introduced in the *Literature Review*. Finally, the *Conclusions and Future Research* chapter summarizes the achievements and contributions of the HFIRM prototype to the field of human factors and prioritizes opportunities for future development cycles.

Literature Review

Human error is responsible for 85% of naval accidents costing about $570 million annually (Steber, 2008). In the aviation domain 80% of accidents result from human error (Johnson, 2003). In 2000 medical error gained widespread attention when The Institute of Medicine estimated that human error results in 44,000 to 98,000 patient deaths annually in the U.S. (Kohn, Corrigan, & Donaldson, 2000). Prominent accidents in the field of space exploration, such as the Challenger explosion, and in the field of nuclear power, such as Three Mile Island, have also been attributed to human error. As a result of the enormous cost of human error, both financial and human, substantial research has been conducted to model and analyze human performance and human error in complex, safety-critical, and high-risk systems. These models and analysis tools vary in their purpose, the sophistication of their content, and the knowledge organization techniques that they employ. This literature review provides a brief comparative analysis of the key concepts and research that have contributed to the theoretical foundation of this research.

Human Factors Concepts

This section provides a brief overview of key human factors concepts that are fundamental to the field of human factors in general, and to this research in particular.

Human factors engineering is the study of the factors that enhance performance, increase safety, and increase user satisfaction during human-system interactions. Human factors engineers apply information from the fields of engineering psychology, cognitive engineering, and ergonomics to develop tools that improve system performance (Wickens et al., 2004). A central concern of human factors engineers is minimizing the risk of human error, either through prevention or through controlling its effect on system performance through the design of error tolerant systems.

Human error is described by James Reason as an occasion, "…in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency," (Reason, 1990). At the behavioral level, Reason categorizes types of errors by their easily observable features into slips, lapses, and mistakes. Slips and lapses are execution errors, while mistakes are intended actions that failed to produce the desired result (Reason 1990).

In order to better understand the causes of human error, researchers have examined the fundamental limitations of the human mind and body that result in human fallibility, i.e. the liability to err or to mislead[2] (Oxford University Press, 1989). Human fallibilities arise out of characteristics of human cognitive and physical mechanisms, and the way they are utilized to accomplish tasks. One widely accepted way to represent human cognition is by differentiating stages of human information processing. Stage models of human information processing represent the cognitive processes that occur as humans translate raw sensory stimuli into reasoned decisions and actions. The way specific stages are defined varies between models. The model that informs this research is derived from the field of psychology, and utilized by Reason (1987) in his framework for classifying errors. The cognitive domains used by Reason to represent the stages of human information processing are sensory registration, input selection, temporary memory (including prospective memory), long-term memory, recognition processes, judgmental processes, inferential processes, and action control. An alternative but similar framework is presented by Wickens and Hollands (2000) and includes sensory processing (includes short-term sensory store), perception, attention resources, working memory, cognition, long-term memory, response selection, response execution, and feedback from the system environment.

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[2] Full Oxford English Dictionary definition of fallibility: "The state or fact of being fallible; liability to err or to mislead (in mod. usage limited to the former); an instance of the same," (Oxford University Press, 1989).

Analytical Techniques

Existing frameworks for analyzing and modeling human performance and human error utilize a number of different organizational structures, including among others, the taxonomy, the hierarchical task analysis, the event tree, and ontology-based databases. The organizational scheme that each model employs is a critical concern because it determines the type of information and the range of relationships that can be represented. Domain specialists and human factors experts have attempted to utilize existing organizational structures to model human error with varying degree of rigor and success. This section provides an overview of several relevant analysis frameworks and knowledge organization techniques.

The taxonomy is a frequently used organizational structure for human error classification (Rasmussen, 1986, Makeham et al, 2002, Woods and Doan-Johnson, 2002, Wandke, 2005, Weigmann and Shappell, 1997, etc.). Taxonomies permit the classification of information into hierarchical relationship structures and can be modified or customized in order to accommodate general or specific subject areas. Additionally, the structure of the taxonomy can be used to express a wide range of hierarchical (i.e. parent-child) relationships. Hierarchical relationships classify entities in the domain of interest using specific criteria. The “child” must satisfy the same constraints as the “parent,” plus one or more additional criteria (Plosker, 2005). Due to its structural simplicity and comprehensibility, the taxonomy is frequently used to model human performance. However, the hierarchical structure of the taxonomy limits the sophistication of the relationships that it can represent.

A second relevant organizational structure is the task analysis method, which arose from the practical need to understand and improve the goal-oriented performance of humans in work systems. Task analysis is a reductionist technique that involves delineating system goals and identifying the actions (both physical and cognitive) needed to achieve those system goals. Additionally, analysts define the success criteria for the goal-oriented actions (Shepard, 2001).

Hierarchical task analysis builds on task analysis principles to provide a formalized framework for examining tasks. In hierarchical tasks analysis, tasks are defined by goals as opposed to actions. System processes are decomposed into a hierarchy of goals and sub-goals, facilitating the systematic analysis of factors that may reduce the probability of successfully achieving the goals (Shepard, 2003).

The basic hierarchical task analysis framework serves as the foundation for a number of sophisticated modeling techniques. One such model is the Integration Definition for Function Modeling (IDEF0) standard published by the National Institute of Standards and Technology. IDEF0 is a technique used to model the primary functions of proposed systems. IDEF0 defines a method for translating system goals into hierarchical task analysis without specifying implementation decisions. This process allows for the procedural analysis of tasks by defining the steps (both mental and physical) that an operator must go through to accomplish system goals, but does not specify how they will be accomplished. Tasks are organized by functional dependency and identify the inputs, outputs, controls, and mechanisms for each task. NIST requires that the IDEF0 framework be generic, rigorous, concise, conceptual, and flexible (NIST 1993).

The fault tree is a logical diagram that is used to model and analyze failure processes in goal-oriented systems. Each fault tree is created to analyze a single adverse event. The undesired effect is the root of the tree, and analysts work in a top-down fashion to identify causal situations. The event tree is very similar to the fault tree in structure; however the event tree approaches the analysis from the opposite direction, using an undesired initiator as its root. The trigger is used to identify resulting events and eventually a final consequence. Probabilities can be assigned to the branches of both fault trees and event trees in order to conduct a probabilistic risk assessment (Haasl, 1965).

Failure Modes and Effect Analysis is a procedure for identifying failure modes and classifying their effects. Although the tool originally emerged in the manufacturing industry, analysts have adapted it for use across industries and disciplines. A failure is defined as an error or defect that affects system goals. FMEA can be used for both prospective and retrospective error analysis, so failures can be either potential or actual. A failure mode is the general way a failure occurs.

The failure effect is the immediate consequence of the failure. FMEA is a flexible tool, and can be applied to systems, designs, products, processes, services, and machines (Stamatis, 1995). The FMEA framework can be tremendously useful for systematically evaluating the effects of failures.

Perhaps the most relevant knowledge organization technique to this research is the ontology, which will now be discussed in some depth. The ontology is a sophisticated and robust schema that is growing in recognition as an effective framework for organizing, standardizing, and representing different types of relationships within a universe of discourse. Hussain et al. (2006) define ontology as an “explicit formalization and conceptual specification of knowledge representation.”

Many simple ontologies are structurally similar to taxonomies. However, while a taxonomy is limited to hierarchical classification, the ontology structure can accommodate a variety of different relationships which explicitly define and formally represent the domain of interest. Defining characteristics of any ontology are conceptualization complexity and the expressiveness of the ontology language (Cross and Pal, 2005).

Gruber (1995) posits that the primary role of an ontology is to support knowledge sharing activities, and he proposes design criteria to guide the development of ontologies for this purpose. The criteria are clarity, coherence, extendibility, minimal encoding bias, and minimal ontological commitment. Gruber (1995) acknowledges that trade-offs between these criteria will be necessary during ontology development.

Ontology development entails the classification of concepts and the identification of attributes used to define the relationships between concepts. Defining relationships between data concepts requires integrating the available data within the domain of interest. Hussain et al (2006) propose a conceptual framework for synthesizing information from many researchers into a trustworthy ontology. Their method includes holding data in an intermediate level until it can be validated and appropriately incorporated into the ontology by a qualified administrator. This method encourages collaboration while controlling for quality.

Advances in information technology have accelerated the demand for knowledge sharing tools. Ontologies are powerful tools for organizing, recording, managing, and sharing information. An ontology may stand alone, or it may serve as the architectural foundation for a database. An ontology describes a basic theory of what exists within a domain of interest, and a database can be developed to store the information described conceptually by the ontology. The ontology defines concepts and relationships, while the database contains instances of those ontological concepts (Castano, 1999). The robustness and analytical potential of both tools can be increased when the knowledge-sharing capabilities of the ontology are combined with the data-sharing power of database technologies.

Modeling Approaches

The most effective knowledge organization structure for any given methodology will depend on the objectives of the model. The ultimate objective of all the human performance models addressed in this review is to reduce the negative effects of human error. The strategies employed by different models to reach that goal vary along a number of relevant dimensions. This review will introduce the human error identification tools, performance models, and analysis techniques relevant to the development of the methodology proposed in this thesis.

The strategies employed by analysts in the development of human performance methodologies vary as a result of the different contributions that they hope to make. For the purposes of this review, the two approaches that are most relevant will be referred to as the identification approach and the remediation approach. These two approaches represent opposite ends of a spectrum, and each approach has strengths and shortcomings. Identification models identify and classify errors and/or their effects. In contrast, remediation models correct faults through either countermeasures or redesign. Identification models are usually knowledge-oriented, contributing to the understanding of human performance and human error. Remediation models are often more action-oriented, and primarily concerned with implementing design changes and countermeasures. One common weakness of models that adopt an identification approach is that they allocate inadequate attention to practical interventions. In contrast, models that focus solely on remediation risk rushing to solution without adequately scoping the causal factors responsible for the error. These models are not mutually exclusive, and some sophisticated models successfully incorporate both identification and remediation. Both approaches inform this research.

One critical distinction between existing human performance models is the extent to which they are intended to expose the underlying causes of human error. Reason (1987) distinguishes between the behavioral, the contextual, and conceptual levels of classification. The behavioral level classifies the observable "What?" element of human error. The contextual level classifies the "How?" and the conceptual level classifies the "Why?" elements of human error. Cause-oriented methodologies address the "Why?" and sometimes the "How?" questions of human error. They tend to encourage human-factors driven analyses of systems by focusing analyst attention on the cognitive and physical strategies that operators employ during task activity.

The objective of effect-oriented methodologies is to address the behavioral, "What?" questions of human error. In contrast to cause-oriented models, effect-oriented models focus on identifying and classifying observable errors and/ or their consequences. While the goal of cause-oriented methodologies usually includes preventing human errors, effect-oriented frameworks focus on identifying ways to control and minimize the effects of human error through countermeasures and error-tolerant design.

Regardless of where they fall in the identification-remediation and cause-effect dimension discussed above, methodologies may be designed to analyze events that have already occurred, or to anticipate events that may occur in the future. For example, effect-oriented models may either retrospectively address actual events, or prospectively address potential events. Retrospective effect-oriented models are limited to the examination of observed errors and accidents, and are frequently domain-specific. Effect-oriented models that are intended for prospective analysis and consequence prediction must rely on sources external to the model for information about the causal and contributing factors of the errors being analyzed.

An additional factor that significantly affects the practical application of any human performance modeling technique is the breadth of the domain that the model describes. Generalizable frameworks are applicable across domains. Domain-specific frameworks are applicable only to specific industries, fields, or environments. As a result, generalizable methods must be rooted in concepts that transcend specific domains, while domain-specific classification schemas are more likely to be derived from the data being analyzed.

The final critical dimension describes the procedural rigor of proposed methodologies, and the extent to which information necessary for the analysis is included in the model. Ad-hoc methodologies either loosely define procedures for implementation, or information necessary to the analysis is not included in the model. As a result, the successful implementation of the methodology relies heavily on the expertise of the operator. Highly systematic methods rigorously define implementation procedures, and/or include the information necessary to conduct the analysis in the model.

Also important to this review is the extent to which a model is rooted in human factors knowledge, the ease of application of the model to a real-world system, and the efficiency of the methodology. The dimensions and trends introduced above describe general characteristics of many methodologies, and are not intended to gauge the effectiveness of any given model in achieving its intended objectives. Where a particular model is positioned along these dimensions depends on both its purpose and its scope. Some models are intentionally limited in their scope. These descriptors have been articulated for the purposes of this research because they facilitate the analysis and comparison of the respective strengths and weaknesses of each model, and lend insight into how each might be augmented.

Existing methodologies for analyzing human performance and human error vary along five critical dimensions which are described in Table 1. Many of the seminal methodologies addressed in this review are elegant solutions that are positioned in the more sophisticated extremes of these dimensions.

Table 1: Critical Dimensions of Human Performance Models

CRITICAL DIMENSIONS OF HUMAN PERFORMANCE MODELS	
Identification	**Remediation**
• Knowledge-oriented • Identify and classify errors and their effects	• Action-oriented • Prevent errors and correct faults through either countermeasures or redesign
Effect-oriented	**Cause-oriented**
• Analysis primarily considers observable behavioral errors and adverse events	• Analysis primarily considers the underlying conceptual and contextual causes of human error
Domain-specific	**Generalizable**
• Applicable to a limited range of industries, fields, or environments	• Applicable across domains
Retrospective	**Prospective**
• Address events that occurred in the past • Applicable only after implementation	• Anticipate and predict future events • Applicable during the design phase
Ad-hoc	**Systematic**
• Procedures for implementation are loosely defined • Information necessary to the analysis is external to the model	• Procedures for implementation are rigorously defined • Information necessary for the analysis is included in the model

These dimensions have been defined specifically to facilitate this review. Other analysts have differentiated existing methodologies according to their research goals, and these categorizations are not inconsistent with the categories utilized here. For example, Weigmann and Shappell (2001) considered the strengths and weaknesses of extant strategies for modeling human errors in the context of aviation. The five prominent perspectives on human error evaluated by Weigmann and Shappell are cognitive, ergonomic and system design, aero-medical, psychosocial, and organizational. Discussion of the weaknesses of each perspective focuses on the ability of each method to distinguish between factors that cause, versus contribute to, error in systems. Based on the strengths and weaknesses of each perspective, Weigmann and Shappell propose five criteria for evaluating error frameworks. These criteria are reliability, comprehensiveness, diagnosticity, usability, and construct validity. Construct validity is distinguished as the most important characteristic of an error framework, and is defined as the extent to which a framework exposes the underlying causes of adverse events. Construct validity is roughly equivalent to the cause-effect orientation utilized in this review, and the reliability criterion is related to the ad-hoc-systematic dimension.

Existing Models

The following section provides a brief introduction to extant methodologies that have informed this research, and identifies how they align with the critical dimension discussed in the Modeling approaches section. James Reason and Jens Rasmussen are two of the pre-eminent scholars in the field of human error, and both have proposed seminal models of human error. These will be addressed first because they serve as the theoretical foundation for numerous other methodologies.

In response to the propagation of error taxonomies, Reason (1987) designed a framework for classifying errors. This framework defines the critical elements that a taxonomy of human error should contain to effectively address human error. These important elements are basic error tendencies, information-processing domains, primary error groupings, situational factors, and predictable error forms. Reason defines five basic error tendencies, which constitute the root of most human errors. The interactions between these basic error tendencies and eight information processing domains result in eight primary error groupings. Reason then introduces situational factors, which interact with the primary error groupings to influence the probability that one or more of the primary error forms will be manifested. These cause-oriented classification dimensions encompass both the conceptual and contextual roots of human error.

Reason's Generic Error-Modeling System (GEMS) defines three basic conceptual error types (skill-based slips and lapses, rule-based, and knowledge-based errors) and provides a theoretical classification scheme for identifying and organizing errors based on these categories. Error types are related to the cognitive stages during which they occur and the operator's level of cognitive control (Reason, 1990). Reason's GEMS model provides a cause-oriented framework through which to analyze human error across domains, and his expertise based classifications are used in numerous subsequent models (Makeham et al, 2002, Militello and Hutton, 1998, Zapf et al, 1992, Sutcliffe and Rugg, 1998).

Reason also proposes the Latent Error Model of Accident Causation (Reason, 1990) which defines a framework for tracing a causal sequence of failures from latent preconditions to unsafe acts. The model identifies four levels of system factors that may contribute to failures: organizational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts. In his famous "Swiss cheese" analogy presented in Figure 1, Reason describes how these factors may precipitate system failures when they align (Reason, 1990).

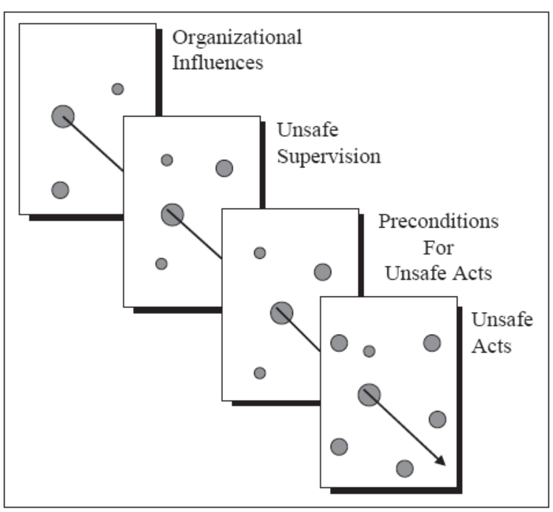


Figure 1: Reason's Latent Error Model of Accident Causation (Reason, 1990)

Rasmussen's (1986) Taxonomy for Describing Human Malfunctions portrays the factors and elements that must be considered in order to explain human behavior and human error. The purpose of this taxonomy is to facilitate the application of data extracted from accident reports to the design of reliable systems. Rasmussen traces behavior backwards from an external human malfunction (i.e. human error), through the internal human malfunction, to the mechanism of human malfunction, in order to identify the cause of the human malfunction. Rasmussen also identifies the factors that affect human performance, situation factors, and personnel tasks types that contribute to the eventual human malfunction (Rasmussen, 1986).

Reason (1990) and Rasmussen (1986) provide highly sophisticated, theoretical models of human error that are cause-oriented, rooted in human factors principles, and applicable across domains. Their models are highly sophisticated human error identification tools, and their successful implementation relies heavily on the expertise of the analyst. The practical application of these theoretical models is particularly problematic in environments where information regarding errors and accidents is incomplete or unavailable. Many analysts have therefore opted for a simpler, more concrete approach to human error identification.

A straightforward example of a retrospective analysis that utilizes an identification approach is the taxonomy developed by Woods and Doan-Johnson (2002) to classify nursing practice errors. Their technique involves analyzing medical accident reports, and identifying and classifying nursing errors. Their study analyzes 21 nursing errors, grouping them into 8 general categories of nursing errors. Their analysis is effects-oriented, ad-hoc, and retrospective. While their analysis is not rooted in human factors principles, it provides the basic error information that would be required to perform a more sophisticated error analysis.

Makeham et al (2002) develop a taxonomy from case-study research in order to develop strategies to improve patient safety in the field of general practice medicine. They employ a similar technique to Woods and Doan-Johnson (2002), but also incorporate human factors principles into their classification scheme. Their report classifies 435 reported errors into 171 error types. The first level classifications are “process errors” and “knowledge and skill errors.” These error categories are loosely derived from the error categories defined by Reason (1990), rooting the taxonomy in human factors principles. These first-level categories are then sub-divided into domain-specific tasks during which errors were observed. This retrospective error and task analysis provides a means of identifying where in the medical process (i.e. diagnosis, treatment, etc.) errors occurred.

The case-study method used by both Woods and Doan-Johnson (2002) and Makeham et al (2002) result in domain-specific taxonomies of error. Sutcliffe and Rugg (1998) propose a generic technique for modeling cognitive processes that is applicable across domains. The first step defined by their method is to organize observed errors into an error taxonomy. Next, analysts gather information about the expertise of the users and the levels of cognitive processing that they employ, and examine the social and organizational factors. This analysis in based on Reason’s (1990) premise that the expertise of the user significantly impacts the type of error that individual will make. The model developed by Sutcliffe and Rugg (1998) is an example of a cause-oriented taxonomy that incorporates domain-specific information in order to conduct an analysis driven by human factors principles. Like the domain-specific errors taxonomies previously discussed (Woods and Doan-Johnson, 2002, Makeham et al, 2002) this model focuses on the identification of errors within a system. While the ultimate purpose of these models is to support the reduction of errors and adverse events, they do not explicitly identify appropriate error remediation techniques.

Lim (1996) proposes the Method for Usability Engineering (MUSE), a strong example of a principled, generalizable method that integrates the identification and remediation approaches to prospectively identify and prevent human error. MUSE is a human factors methodology which employs the task analysis structure to systematically drive user-centered design. The first phase of MUSE is information elicitation, during which analysts model system goals in a task analysis. In the second phase analysts synthesize human factors design goals into statements of user needs. Third, analysts integrate user needs with the system functions to form a task model. The final stage is the device implementation phase, during which analysts develop specifications for implementation (Lim, 1996). The successful implementation of MUSE during the design of an air traffic control system (Marti, 1998) provides evidence that the method is sufficiently robust to adequately model complex systems.

Shepard (1998) presents a highly systematic methodology for developing a hierarchal task analyses. The first step in the process is to identify and formally state a particular system goal, explore the constraints of the goal, and evaluate the acceptability of the potential system outcomes. This phase involves subject matter experts by asking them to describe the cognitive strategies involved in completing tasks, thereby facilitating the incorporation of cognitive processes in the task analysis as appropriate. If the first step identifies potential outcomes that are unacceptable, then the operation and system interactions are examined and the tasks or goals are changed to prevent the unacceptable outcome. This task analysis methodology is intended to focus design attention on the critical points in the system where errors and adverse events are most likely (Shepard, 1998). Much like MUSE (Lim, 1996), this method supports both the identification and remediation of potential adverse events by directing analyst attention and design efforts to the points in the system where the potential for errors is greatest.

Militello and Hutton (1998), propose a practical adaptation of Shepard’s (1998) methodology for conducting a hierarchical task analysis. Their technique, called Applied Cognitive Task Analysis, is a method for identifying the cognitive skills needed to a perform task. The method consists of a series of three structured interviews conducted with subject matter experts. The objective of the first interview is to create a task diagram which decomposes the system goals into processes. The second interview gathers information about which components of the task are difficult for novices versus experts. Finally, a simulation interview is conducted during which the subject matter expert is presented with a challenging scenario and asked to describe the cognitive processes and coping strategies that may be employed by operators of different skills levels when addressing such a scenario. The information regarding cognitive processes is mapped to categories of decision making, facilitating the targeted implementation of human factors principles in support of these decision making processes. Like Shepard (1998), Militello and Hutton (1998) advocate the systematic solicitation of subject matter expert input to inform the methodical development of hierarchal task analyses. The resulting modeling technique is cause-oriented, human-factors driven, and systematic.

Like Lim (1996) and Shepard (1998), Wandke (2005) also models cognitive processes in a hierarchal framework. Wandke (2005) proposes a taxonomy for assistance in human-machine interaction that is intended to anticipate and prevent human error. The first level of Wandke's hierarchy is divided into human information processing stages: motivation, perception, information integration, decision making, action execution, and processing feedback. Compatible types of user-support and technical assistance are then assigned to each of the six actions stages (Wandke, 2005). This human-factors rooted methodology prospectively identifies potential human errors in order to promote user-centered design.

Weigmann and Shappell (1997) also employ a taxonomy structure to create a human error analysis technique that is rooted in human factors theory. In order to assess the applicability of extant modeling techniques Weigmann and Shappell classify post accident data using three conceptual human error frameworks and measure the ability of each framework to categorize the observed errors. They restructured the US Navy and Marine Corps error database using a stage model of information processing, Rasmussen's (1986) model of internal human malfunction, and Reason's model of unsafe acts (1990). It was possible to classify over 85% of the errors in the database using each of the three models, however each model failed to fully account for performance shaping factors and organizational factors.

Based on their research in classifying the errors in the US Navy and Marine Corps database, Weigmann and Shappell (1997) proposed their Taxonomy of

Unsafe Operations. The Taxonomy of Unsafe Operations is a classification scheme for post-accident data analysis. Their sequential framework considers unsafe acts, unsafe conditions, and unsafe operations. The Taxonomy of Unsafe Operations is a cause-oriented classification scheme intended to facilitate focused intervention by exposing the underlying causes of human error. They identified adaptation for prospective analysis and prevention of adverse events as an opportunity for further development of their Taxonomy of Unsafe Operations. This model provides a comprehensive framework for classifying observed errors based on their underlying causes. However, because the precise relationships and interdependencies between these elements are not defined, its successful prospective application to real-world systems relies heavily on the insight and expertise of the analyst.

Bogner (2002) incorporates many of the same system factors that are identified by Weigmann and Shappell (1997) into an unconventional structure to analyze error in medical systems. The Systems Approach to Medical Error (SAME) is intended to promote the identification and modification of systemic conditions which contribute to error. Bogner models the system as a series of concentric circles, with the innermost circles having the most immediate effect on the care provider. Each circle represents an aspect of the system. The innermost elements are the conditions of the care provider (expertise, fatigue), the patient (anxiety, age, weight), and the means for providing care (technological sophistication, cognitive workload, time of use). Moving outwards, system elements represented are ambient environment (illumination, noise), social (communications, professional culture), physical setting (room setup and equipment placement), organization (workload and organizational culture), and legal/regulatory/cultural (litigation, reimbursement). All of the system elements have the potential to send error-provoking ripples throughout the system, eventually impacting human performance. The primary contribution of this model is its thorough description of system factors and the acknowledgement of their interdependencies. Similar to Weigmann and Shappell's Taxonomy of Unsafe

Operations, the practical use of SAME is difficult because it lacks a systematic procedure for application to a real-world system.

The Task Analysis for Error Identification (TAFEI) integrates the task analysis structure with human error identification techniques (Stanton & Baber 2005). TAFEI is a methodology for error prediction that follows a three step process. First, analysts decompose system processes to create a hierarchal task analysis. Next, analysts develop a state-space diagram to represent the operations of the system, and map the state-space diagram to the hierarchal task analysis. The third and most novel step of the TAFEI is the creation of a transition matrix which explicitly considers the state transitions that can result from each task and categorizes them as either impossible, possible but illegal (undesirable), or possible and legal (desirable). The essential premise of the TAFEI model is that errors in simple human-machine systems arise out of human-machine interactions. The transition matrix models that interaction space, ideally identifying each opportunity for a transition to lead to an unexpected state or error (Stanton & Baber 2005). TAFEI is a highly systematic method that utilizes system constraints, instead of human factors design principles, to prevent potential errors. While this effects-oriented model lacks a strong foundation in human factors principles, it is both rigorous and generalizable across the domain of simple human-computer interactions.

User expertise drives the hierarchical structure of the taxonomy designed by Zapf et al (1992). This theoretical model of human-computer interaction describes human errors as usability mismatches between the system and the operator. The type and frequency of usability mismatch (error) observed is considered to be dependent on the expertise of the operator (Zapf et al 1992). Zapf's taxonomy is primarily concerned with the identification of errors (as opposed to remediation of errors), and is cause-oriented because it is organized around the underlying cognitive strategies which may precipitate human error. Hyland and Vrazalic (2003) apply the taxonomy developed by Zapf et al (1992) in the categorization of errors observed during usability testing of a computer application. The results of the study generally validate the predictions of the taxonomy.

Perhaps the most sophisticated methodology for prospective identification of human errors that utilizes the hierarchical task analysis structure is Embrey's (1986) Systematic Human Error Reduction and Prediction Approach (SHERPA). Like Zapf et al (1992) Embrey also models human error in human-computer interaction. However, while the model proposed by Zapf et al maps tasks to causal errors by analyzing user expertise, Embrey's model analyzes action stages. SHERPA is a method for human error identification that is based on the hierarchal task analysis. Analysts create the task analysis by breaking down upper-level goals into subordinate goals, and by identifying the sequence in which tasks are conducted to achieve these goals. Analysts then assign each task to one of five action categories which are derived from human information processing stages, and identify potential human errors in each stage. The final steps of the process consist of an error consequence analysis and an error recovery analysis (Embrey 1986). SHERPA is a prospective, systematic, cause-oriented analysis technique that is rooted in human factors principles.

Validity tests provide evidence that the SHERPA technique is reasonably effective in predicting errors (Baber and Stanton 1996; Stanton and Stevenage 1998). Baber and Stanton (1996) provided confirming evidence for the validity of the SHERPA method by comparing errors predicted by an expert analyst with those observed during 300 interactions with a ticket machine. This study was replicated and extended by Stanton and Stevenage (1998) who compared the accuracy of predictions made by an untrained control group with the accuracy of predictions made by an experimental group trained in basic human factors who used the SHERPA technique. Results showed that while the group using the SHERPA technique missed fewer errors than the untrained control group, the SHERPA group still missed errors that are indicated by human factors heuristics (Stanton and Stevenage, 1998). More recently, SHERPA has been successfully used to predict human error in the fields of both aviation (Harris, 2005) and medicine (Lane, 2006).

Most other models discussed in this review that utilize the hierarchical task analysis structure are confined in scope to the analysis of individual tasks (Stanton & Baber, 2005, Embrey, 1986, and Zapf et al., 1992). In contrast, Rothrock et al (2005) employ hierarchical task analysis to examine team performance factors in complex work environments. They present a theoretical framework for classifying tasks and outcomes, and a means for assessing team task complexity based on subjective evaluations of workload. The premise of this model is that it is possible to break down team tasks into individual components, and to relate those individual components back to the team objective. Because this is a fundamentally reductionist model, its predictions do not anticipate emergent factors. Additionally, it relies on subjective workload assessments, which may vary between operators.

Rognin et al. (2000) also focus on team performance, but use a different analytical structure than Rothrock et al (2005). Rognin et al. introduce the concept of the collective regulatory loop to describe the relationships between task organization, information sharing, and active and informed participation in error prevention. Their model of team performance attempts to describe the relationships between function allocation, social factors, and human errors in complex cooperative systems. They argue that in cooperative work environments, function allocation directly impacts the quality of communication between operators. Effective communication facilitates a broader awareness of the system state. This heightened awareness allows operators to act as regulators, identifying and preventing potential system errors. Rognin et al. propose a conceptual framework for evaluating the potential for error in a system based on the extent to which task organization in the system encourages the development of regulatory loops. By integrating social factors into their error model, Rognin et al (2002) incorporate the impact of collective system awareness in environments where concurrent and interdependent tasks are performed.

Although the majority of the methodologies introduced in this review utilize a hierarchical task analysis structure, the tree diagram can also be an extremely effective risk analysis tool because it allows analysts to track errors and causal factors as they propagate themselves through the system. Fault Tree Analysis (FTA) facilitates the tracing of errors back through the target system in order to isolate causal factors. Traditionally used to analyze specific adverse events, Hyman (2002) utilizes FTA to conduct a generic analysis of errors occurring during the use of medical devices. The concept underlying Hyman's (2002) application of the FTA is that error can be systematically evaluated in a general way, revealing controllable system factors that contribute to the realization of adverse events. Hyman's technique assumes the existence of a generic "user error" as a starting point for identifying relationships between system variables. This application of the FTA includes the pictorial representation of generic causal events and system conditions, and is intended to promote awareness and prevention of error events. Hyman's FTA takes a prospective approach to the identification of human error that is applicable across domains.

Koval and Floyd (1998) use an event tree structure to model error in human-machine systems using an accident-injury sequence framework. The root of event trees is a trigger or cause. In this model the initiating event is defined generically as "Exposure to hazardous situation" (Koval and Floyd 1998). The operator's actions determine the subsequent events, modeled as an action path. At each action stage the framework identifies human factors that could influence the operator's ability to implement prevention strategies (Koval and Floyd 1998). The event tree pushes analyst attention to the consequences of trigger events. As a result this model is better suited to identify opportunities to implement countermeasures than it is to providing insight into how to prevent the original error.

Some tools intended to improve system performance focus exclusively on preventing human error by incorporating principles of user-centered design during the design phase. These tools are remediation methods in the sense that they attempt to correct faults before they precipitate human error by applying human factors principles in the design phase. Unlike the methodologies discussed in this review that attempt to model human performance, these design tools do not provide a framework for the focused analysis of specific systemic factors which may increase the probability of human error. However, human factors standards and design rules can and should be used for guidance during the design phase. One such design aid is provided by Norman (1983). The purpose of Norman's research is to both minimize errors and mitigate the effect of errors that do occur. Norman's design rules are based on commonly observed human errors when interacting with computer systems. These principles of system design emphasize the importance of considering human abilities and limitations when creating systems where humans play an important role.

While Norman's design rules are applicable only to human-computer interactions, some human factors standards and guidelines apply across disciplines. One such set of guidelines is the "International Standards for HCI and Usability" (Bevan, 2001) which contribute to error reduction by incorporating principles of usability in the design phase. These standards are developed through a rigorous, iterative process that engages experts in the synthesis of human factors and ergonomics knowledge. By design, these standards define general principles and metrics for assuring the incorporation of all necessary user-centered design considerations. These standards do not offer solutions or implementation specifications (Bevan, 2001). When used appropriately as a design tool, human factors standards can prospectively minimize the risk of human error in a system by ensuring human factors are considered.

The ad-hoc-systematic dimension of human performance models describes the extent to which a methodology includes both the information and the implementation procedure necessary for its application to real-world systems. This dimension is an important determinant of how effectively and consistently the methodology will be utilized by analysts. Several existing frameworks provide highly systematic, principled, information-rich human error analysis techniques.

The systemic vulnerability analysis technique proposed by Funk et al. (in preparation) is intended to support the identification of vulnerabilities in complex systems by matching functional characteristics of the system with characteristics of errors. Functional characteristics of the system are drawn from a modeling methodology adapted from IDEF0. Funk et al. propose a comprehensive human error taxonomy to identify relevant error characteristics. This taxonomy expands on previous error taxonomies by incorporating a wide range of detailed generic error information. During the application phase, human factors experts and system experts translate the generic error information into domain-specific language. Errors are categorized using seven parameters: error name, whether the error occurs at the individual or team level, type of task that is subject to the error, goal characteristics, human information processing stage (for individual errors), team interaction mode (for team errors), and factors that affect the likelihood of the error (Funk et al., in preparation).

Computer- based information technologies allow designers to increase the quantity and accessibility of the information that is incorporated into their methodologies. Modeling software, simulation programs, and databases, facilitate the development of systematic, information-rich analysis techniques. These powerful technologies have been employed in the development of both identification and remediation tools, and they contribute significantly to the development of the methodology presented in this research.

COSIMO (Cacciabue et al., 1992) is a systematic technique that utilizes advanced information technology to identify potential human errors. COSIMO is a comprehensive cognitive simulation model of human behavior in complex work environments. Cacciabue et al. (1992) allow for the unpredictability of human behavior in their model of human cognition through the development of a cognitive simulation tool. COSIMO identifies and models the cognitive functions performed by an operator during accident management. The simulation assists in the analysis of accident evolution and the identification of difficult problem solving situations within systems. In preliminary validity tests, evidence supports the accuracy of COSIMO's predictions of human action (Cacciabue et al., 1992).

In addition to allowing for the development of robust computer-based human error identification tools such as COSIMO, information technology has also contributed to the development of powerful error remediation tools. The HFYI Design CoPilot is a web-based decision-support tool for addressing human factors considerations during the aircraft flight deck design and certification process (Research Integrations, 2008). The foundation of the Design CoPilot is a database of information that defines relationships between FAA regulations and guidance materials and human factors considerations and design guidelines. The user-interface is highly sophisticated, allowing users to choose from a variety of flexible searches to access information regarding regulations, human factors considerations, and design guidelines. This domain-specific application is organized around the primary flight deck system components: controls, displays, equipment, systems, tasks and procedures, and testing assumptions. The HFYI Design CoPilot is a robust decision-support tool that encourages user-centered design by making human factors design considerations available to users.

In Tables 2-4, each of the models addressed in this review is assessed based on the critical dimensions of human performance models introduced in the Modeling Approaches section. The Ad-hoc/ Systematic dimension is judged by two primary criteria: the extent to which procedures for implementation are rigorously defined, and if the information necessary for the analysis is included in the model. Table 2 displays the identification models that are intended to classify errors and their effects. Table 3 displays remediation models that focus on preventing errors and correcting faults. Table 4 presents models that incorporate both the Identification and Remediation of errors.

Table 2: Identification models categorized by the critical dimensions of human performance models

Method	**Authors**	**Effect-oriented/ Cause-oriented**	**Domain-specific/ Generalizable**	**Retrospective/ Prospective**	**Ad-hoc/ Systematic**[3]
Generic-Error Modeling System (GEMS)	Reason, 1987	Cause-oriented	Generalizable	Prospective	Systematic (lacks info)
Latent Error Model of Accident Causation	Reason, 1990	Cause-oriented	Generalizable	Prospective	Systematic (lacks info)
Taxonomy for Describing Human Malfunctions	Rasmussen (1986)	Cause-oriented	Generalizable	Prospective	Systematic (lacks info)
Taxonomy of Nursing Practice Errors	Woods and Doan-Johnson (2002)	Effect-oriented	Domain-specific	Retrospective	Ad-hoc
Taxonomy of General Practice Medical Errors	Makeham et al (2002)	Effect-oriented	Domain-specific	Retrospective	Ad-hoc
Generic Expertise Error Model	Sutcliffe and Rugg (1998)	Cause-oriented	Generalizable	Retrospective	Systematic
Taxonomy of Unsafe Operations	Weigmann and Shappell (1997)	Cause-oriented	Domain-specific	Retrospective	Systematic (lacks info)
Systems Approach to Medical Error (	Bogner (2002)	Cause-oriented	Domain-specific	Prospective	Systematic (lacks info)
Error model of human-computer interaction	Zapf et al (1992)	Cause-oriented	Domain-specific	Prospective	Systematic (lacks info)
Team performance task analysis	Rothrock et al (2005)	Cause-oriented	Generalizable (team tasks)	Prospective	Systematic (lacks info)
Collective regulatory loop analysis	Rognin et al (2000)	Cause-oriented	Generalizable (team tasks)	Prospective	Systematic (lacks info)
Fault tree for medical device errors	Hyman (2002)	Cause-oriented	Domain-specific	Prospective	Systematic (lacks info)

[3] The Ad-hoc/ Systematic dimension is judged by two primary criteria: the extent to which procedures for implementation are rigorously defined, and if the information necessary for the analysis is included in the model. If only one of these criteria is present, the model is characterized as systematic and the criterion that is not achieved is noted.

Table 3: Remediation models categorized by the critical dimensions of human performance models

Method	**Authors**	**Effect-oriented/ Cause-oriented**	**Domain-specific/ Generalizable**	**Retrospective/ Prospective**	**Ad-hoc/ Systematic**[4]
Task Analysis for Error Identification	Stanton and Baber (2005)	Effect-oriented	Domain-specific	Prospective	Systematic (lacks info)
Event tree model for human-machine systems	Koval and Floyd (1998)	Effect-oriented	Domain-specific	Prospective	Systematic (lacks info)
Design rules	Norman (1983)	Effect-oriented	Domain-specific	Prospective	Systematic
International Standards for HCI and Usability	Bevan (2001)	Effect-oriented	Generalizable	Prospective	Systematic

[4] The Ad-hoc/ Systematic dimension is judged by two primary criteria: the extent to which procedures for implementation are rigorously defined, and if the information necessary for the analysis is included in the model. If only one of these criteria is present, the model is characterized as systematic and the criterion that is not achieved is noted.

Table 4: Models that address both Identification and Remediation, categorized by the critical dimensions of human performance models

Method	**Authors**	**Effect-oriented/ Cause-oriented**	**Domain-specific/ Generalizable**	**Retrospective/ Prospective**	**Ad-hoc/ Systematic**[5]
Method for Usability Engineering (MUSE)	Lim (1996)	Cause-oriented	Generalizable	Retrospective	Systematic (lacks info)
Hierarchical Task Analysis	Shepard (1998)	Cause-oriented	Generalizable	Retrospective	Systematic (lacks info)
Applied Cognitive Task Analysis	Militello and Hutton (1998)	Cause-oriented	Generalizable	Retrospective	Systematic (lacks info)
Taxonomy for assistance in human-machine interaction	Wandke (2005)	Cause-oriented	Domain-specific	Retrospective	Systematic (lacks info)
Systematic Human Error Reduction and Predication Approach	Embrey (1986)	Cause-oriented	Generalizable	Prospective	Systematic (lacks info)
COSIMO	Cacciabue et al (1992)	Cause-oriented	Generalizable	Prospective	Systematic
HFYI Design CoPilot	Research Integrations (2008)	Cause-oriented	Generalizable	Prospective	Systematic
Systemic Vulnerability Analysis	Funk et al (In Preparation)	Cause-oriented	Generalizable	Prospective	Systematic

As illustrated in Tables 2-4, existing models that analyze human error range in their objectives and strategies. Experts have addressed the challenge of applying human factors knowledge to analyses of complex high-risk systems by developing a variety of methods for reducing both the probability and the adverse effects of human error. Although most of these models attempt to identify and/or remedy human error, the models range in their specific approach, their sophistication, and their utilization of human factors principles.

Several of these models are based on extremely strong foundations of human factors theory, and provide prospective insight into potential causes of human error across industries (Reason, 1990, Rasmussen, 1986). The weakness of

[5] See footnote 4.

these theoretical models is that they are difficult to consistently apply to complex real-world systems. Other models focus on contributing to the identification of errors in a specific field (Wood and Doan-Johnson, 2002, Makeham et al, 2002). While domain-specific models may be useful in the industry for which they were designed; they can't be applied to the general remediation of human error.

The models that have most significantly influenced this research are those that are intended to both prospectively identify and remediate potential errors. These models were presented in Table 4. Methods that incorporate both identification and remediation into a single analysis framework have the potential to make significant contributions to the reduction of human error by bridging theory and practical implementation.

In order to be highly systematic, a model must meet two criteria: define a rigorous procedure for implementation and include relevant human factors information in the model. Inclusion of the appropriate information within the structure of an analysis improves the consistency and accuracy with which the method can be implemented. Methods that do not integrate the human performance knowledge required for their implementation miss a valuable opportunity to provide analysts with memory-aiding information. Systematic models reduce the cognitive workload on analysts by providing analysts with relevant human factors principles and theories. Human error analysis techniques that do not provide such memory-aids are forced to rely exclusively on analyst expertise and memory.

Of the existing models that encompass both identification and remediation, only COSIMO (Cacciabue et al, 1992), HFYI Design CoPilot (Research Integrations, 2008), and Systemic Vulnerability Analysis (Funk et al, In Preparation) attempt to integrate relevant human factors information into the model. None of these three models guides users through an information-driven fully-systematic analysis of the conceptual, contextual, and behavior levels of human error in order to prospectively identify potential human errors. Therefore, there is a significant opportunity to contribute to the field of human factors by developing a methodology that supports both the identification and remediation of potential errors, and that draws on a foundation of human factors knowledge in order to conduct the analysis.

Development

The analytical framework presented in this thesis consists of two primary components: an analysis methodology and a database that supports the systematic implementation of the methodology. This chapter describes the objectives, goals, and development of the Human Fallibility Identification and Remediation Methodology (HFIRM) prototype and the supporting Human Fallibility Database.

Objectives and Goals

The examination of existing methods for analyzing human error presented in the Literature Review chapter revealed that there is a need for a systematically-defined and theory-based analysis procedure that uses an information-driven approach to support the prospective identification and remediation of potential human errors. This research addressed this need by developing and testing a prototype framework that supports the practical application of human factors knowledge to the analysis and design of complex human-machine systems.

Objectives

The HFIRM prototype was designed to meet the following primary objectives:

- Define a generalizable analysis procedure that efficiently facilitates the systematic identification of potential errors in a target task.
- Support the prospective remediation of potential errors by providing analysts with human factors information relevant to designing focused intervention strategies.

The research objectives defined above are multi-faceted and complex. In order to provide more practical guidance for this research and the subsequent assessment of the success of the research, these overarching objectives were decomposed into a number of supporting goals. Each goal articulates and clarifies a specific component of the overarching objectives.

Research Goals

The research goals decompose the high-level research objectives into specific characteristics that the methodological procedure needs to possess and functions that it needs to perform in order to achieve the overarching objectives. These goals provide more practical guidance for design and evaluation of the HFIRM prototype. The following goals are derived directly from the objectives and pertain specifically to the function and design of the analytical framework.

The objective statement for this research is reprinted below. Each underlined and numbered section of the objectives statement results in a specific goal. The goals are enumerated below.

Objectives statement mapped to specific goals:

- Define a generalizable [1] analysis procedure that efficiently [2] facilitates the systematic [3] identification [4] of potential errors in a target task.
- Support the prospective [5] remediation [6] of potential errors by providing analysts with human factors information [7] relevant to designing focused intervention strategies.

Resulting research goals:

[1] Generalizable

a. The methodology will be generalizable so it can be applied across domains.

[2] Efficient

a. The methodology will be efficient, i.e. the ratio of useful information derived from the analysis to the time spent conducting the analysis should be high.

b. The performance analysis will be compatible with at least one existing process modeling technique, so that no novel process modeling technique will need to be developed or adapted in order to conduct the analysis.

[3] Systematic

a. The methodology will define a rigorous procedure for performing an information-driven human performance analysis of the target task.

b. Human performance information that is relevant to the analysis will be contained within the model.

[4] Identification

a. The performance analysis will support the identification of potential human errors and negative system outcomes.

[5] Prospective

a. The performance analysis will be applicable to complex systems in the design phase in order to improve error anticipation, user-centered design, and the development of effective countermeasures.

b. The performance analysis will support the prospective analysis of system and human factors that increase the probability of human error.

[6] Remediation

a. The performance analysis will support the remediation and improvement of procedures, equipment design, and training methods.

[7] Information-driven

a. The performance analysis will draw from a source of human factors information in order to support the identification and remediation of potential human errors and adverse events.

The seven goals above articulate the primary components of the objectives statement. Many of these goals also correspond to dimensions of the Critical Dimensions of Human Performance Models introduced in the Literature Review Chapter. On the identification-remediation continuum, the goal of this methodology is to support both identification and remediation. Although the effect-cause orientation dimension is not explicitly addressed in the goal statements, in order to prospectively identify potential errors the methodology needs to be cause-oriented. The research goals do specify that the methodology should support a generalizable, prospective, systematic analysis. Table 5 shows the research goals mapped to the Critical Dimensions of Human Performance Models, with the stars representing the target for each dimension. The star for the Identification-Remediation dimension is placed in the center of the continuum because the goal of this research is to design an analytical framework that supports both the identification and remediation of human error.

Table 5: The research goals mapped to the Critical Dimensions of Human Performance Models

CRITICAL DIMENSIONS OF HUMAN PERFORMANCE MODELS	
Identification	**Remediation**
☆	
• Knowledge-oriented • Identify and classify errors and their effects	• Action-oriented • Prevent errors and correct faults through either countermeasures or redesign
Effect-oriented	**Cause-oriented**
	☆
• Analysis primarily considers observable behavioral errors and adverse events	• Analysis primarily considers the underlying conceptual and contextual causes of human error
Domain-specific	**Generalizable**
	☆
• Applicable to a limited range of industries, fields, or environments	• Applicable across domains
Retrospective	**Prospective**
	☆
• Address events that occurred in the past • Applicable only after implementation	• Anticipate and predict future events • Applicable during the design phase
Ad-hoc	**Systematic**
	☆
• Procedures for implementation are loosely defined • Information necessary to the analysis is external to the model	• Procedures for implementation are rigorously defined • Information necessary for the analysis is included in the model

KEY	
☆	HFIRM prototype target

The purpose of this section was to clarify the overarching objectives of the HFIRM prototype by defining specific and practical research goals that support the accomplishment of the objectives. These goals were used to guide development activities and to assess the resulting HFIRM prototype. The next section describes the development of the analysis methodology.

Methodology Development

The Human Fallibility Identification and Remediation Methodology (HFIRM) integrates and extends existing theories of human performance and systematically defines a novel approach to the analysis of human error. This section describes the resources required to conduct the analysis, the general strategy employed to meet the research objectives and supporting goals, and the theory-driven development of the analysis methodology, with reference to the principles of human performance and extant research that informed the development of the methodology.

Resource Requirements

The performance analysis was designed to be conducted by a domain or system expert working in cooperation with a human factors engineer. The domain expert provides formal knowledge of system processes and detailed descriptions of the task, the operators, and the environment. The human factors engineer guides the analysis by helping the system expert identify conceptual mechanisms and contextual factors that underlie domain-specific task activities. As a result, application of the analysis tool requires the following resources:

1. Task model of the system to be analyzed
2. Domain or system expert to describe the task
3. Human factors/systems engineer to guide analysis

Methodology Strategy

As discussed in the Literature Review chapter, the fundamental limitations of the human mind and body, and the strategies that we employ to cope with those limitations, result in certain error tendencies. These human fallibilities are the precursors to the human errors that negatively influence goal-oriented performance. Human fallibilities originate in the psychological processes and maladaptive tendencies of humans. As a result, improving human performance requires moderating human fallibilities. Therefore, the strategy that this methodology adopts is to improve human and system performance by supporting the identification of why, when, and how human error tendencies influence task-oriented activity. In order to accomplish this, the Human Fallibility Identification and Remediation Methodology (HFIRM) focuses on articulating the relationships between human fallibilities and the conceptual, contextual, and behavioral levels of human performance. Once identified and defined, those relationships provide an information-rich foundation for performing a principled and systematic performance analysis.

HFIRM consists of three phases. The first phase addresses the conceptual level of human error, and roots the analysis in human factors theory by identifying the human information processing stages involved in the target task. Phase two addresses characteristics of the task, the operator, and the environment that influence the type and probability that certain fallibilities will be manifested. This phase considers the contextual level of human error by identifying how system factors interact with cognitive and physical operations to shape human performance. The third phase presents potential human fallibilities and supports their remediation by providing human factors information relevant to developing theory-based targeted intervention strategies.

Phase One: The conceptual level of human error

Moderating human fallibilities requires addressing their cognitive origins. One widely accepted method for formally representing human cognition is the stage model of human information processing. Each human information processing stage has unique characteristics that result in specific error tendencies. This research articulates the causal relationships between human information processing stages and human fallibilities. The first phase in this methodology requires analysts to identify the human information processing stages employed during the target task. The analysis is then narrowed to consider only those human fallibilities that can be manifested in the cognitive domains that are active during the target task.

Several models of human performance use human information processing stages to classify or identify human error at both the conceptual and contextual level. Reason (1987) deems the inclusion of information-processing domains essential to any taxonomy of human error. Embrey's (1986) SHERPA method requires analysts to assign tasks to action categories that are derived from human information processing stages in order to identify potential human errors. Wandke (2005) classifies human-machine interactions by human information processing stages in order to identify potential human errors and assign compatible user-support.

Numerous variations of the stage model of information processing exist. The stage model utilized in this research is adapted from Reason (1987) and Wickens and Hollands (2000). It differentiates between seven primary cognitive domains which may be employed during task performance: sensory registration, perception, attention allocation, working memory, long-term memory, decision-making, and action control. These human information processing stages are defined in Table 6.

Table 6: Human Information Processing Stages

Human Information Processing Stage	**The cognitive domains which may be operating during different stages of information processing**
Sensory registration	The mental registration of sensory stimuli; limited by the quality of the stimuli and by the sensitivity of human sensory receptors
Perception	The cognitive process of recognizing and assigning a meaningful interpretation to sensory stimuli. This stage is driven by sensory data as well as prior knowledge and expectations. It is distinguished from judgmental and inferential processes because it proceeds quickly and automatically, requiring relatively few cognitive resources.
Attention allocation	Management and allocation of attentional resources to informational channels and cognitive operations
Working memory	Stage during which information is consciously processed to create, update, or revise hypotheses based on newly arriving information. This temporary memory store is resource intensive, limited in capacity, and is extremely vulnerable to disruption and distraction.
Long-term memory	This process of storing (or learning) information creates a more permanent representation of knowledge which can then be retrieved for future use
Decision making	Judgmental and inferential processes used to generate alternatives, form hypotheses, solve problems, and select actions; stage during which available evidence is used to make rational inferences and to evaluate the validity of those inferences
Action control	Utilization of physical or cognitive resources to execute an intended response.

The relationships shared between these seven human information processing stages are diagrammed in Figure 2.

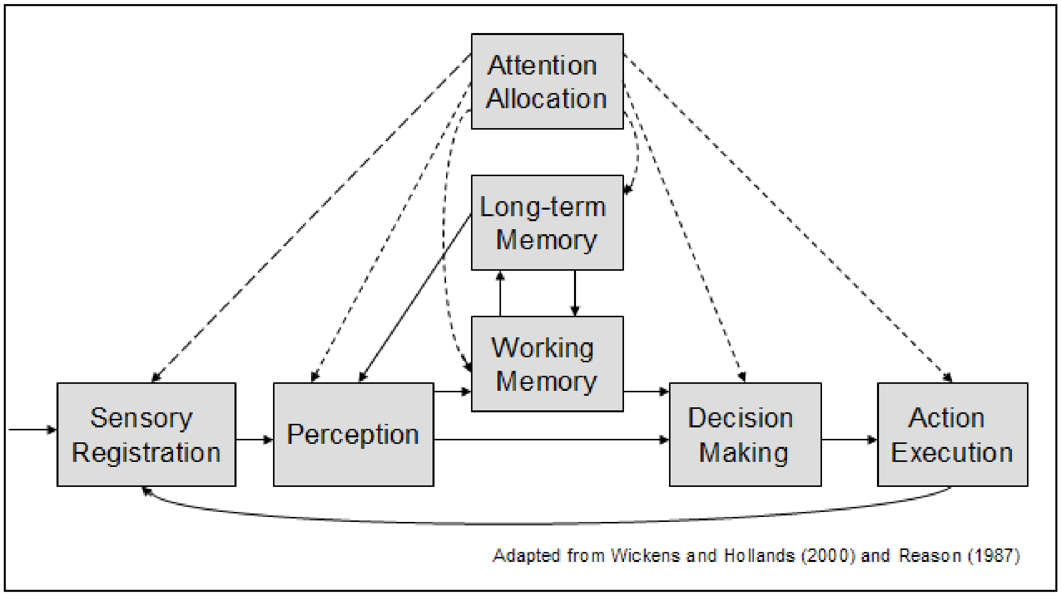
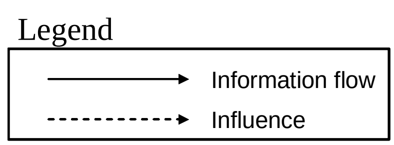


Figure 2: Stage Model of Human Information Processing



Phase Two: The contextual level of human error

The second phase of the HFIRM addresses the cognitive and physical demands placed on operators during the performance of the target task. For the purposes of this research, these demands are broadly referred to as system factors, and include characteristics of the task, the operator, and the environment that influence the probability that a specific human fallibility will be manifested in the target task. Phase two considers the contextual level of human error by identifying how system factors interact with cognitive and physical operations to shape human performance. Delineating the general categories of system variables promotes their use as a memory aid, increasing the probability that all attributes of the system will be explicitly considered and analyzed.

System factors are widely recognized to exert a strong influence on the types of human error that occur and the likelihood of the occurrence. In his Latent Error Model of Accident Causation, Reason (1990) identifies four levels of system factors that contribute to failures: organizational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts. Rasmussen (1986) also acknowledges factors that affect human performance, situation factors, and personnel task types as potential contributors to human error. Weigmann and Shappell (1997) include unsafe acts, unsafe conditions, and unsafe operations in their Taxonomy of Unsafe Operations. The primary purpose of Bogner's (2002) SAME model is to identify the systemic conditions that contribute to medical error in order to remove them. This research integrates system factors presented by Reason (1990), Rasmussen (1986), Weigmann and Shappell (1997), and Bogner (2002). These system factors are described in Table 7.

Table 7: System factors that influence the probability of human error

System Factor	**Description**
1. Task Characteristics	Characteristics of the task being performed (quality and diagnosticity of information, cues, and evidence, time allotted for performance of task, risk, complexity)
2. Operator Attributes	Operator conditions (physiological and cognitive); Operator practices (physical and mental); Operator expertise (skill, rule, or knowledge based processing)
3. Environmental Factors	Factors which contribute to our understanding of the situation in which the task is being performed
a. Physical Setting	Workspace and equipment design, condition, and placement
b. Ambient Environment	Sensory factors such as light, noise, temperature, air pressure, and motion
c. Organizational Factors	Organizational culture (authority structure, leadership and management style, communication practices and mechanisms, training standards, political factors, policy enforcement, procedure design, implementation and standardization, administrative controls, organizational model, incentive system); Team dynamics/Crew Resource Management (composition, cohesion, leadership, motivational techniques employed); Social environment (interactions and relationships between operators, interpersonal communication mechanisms and practices)
d. Professional Factors	Professional norms, accreditation, litigation considerations

In addition to categorizing system factors as characteristics of the task, operator, or environment, this research further differentiates system factors based on how they influence the probability that specific human fallibilities will be manifested. A novel contribution of this research is the classification of relationships between system factors and human fallibilities using the following categories: necessary conditions, contributing conditions, mitigating conditions, and preventative conditions. Necessary Conditions are system factors which must be present in order for a specific human fallibility to be manifested. Preventative conditions are system factors that, if present, prevent the human fallibility from affecting task performance (e.g. design augmentation, countermeasures, and safeguards). Contributing conditions are system factors that increase the probability that the human fallibility will affect task performance. Mitigating conditions are system factors that reduce the probability that the human fallibility will affect task performance, or that reduce the performance decrement. These classifications are presented in Table 8.

Table 8: Relationships between system factors and human fallibilities

Classification	**Relationship Description**
Necessary Conditions	System factors which must be present in order for a specific human fallibility to be manifested
Preventative Conditions	System factors that, if present, prevent a specific human fallibility from being manifested (e.g. countermeasures and safeguards)
Contributing Conditions	System factors that increase the probability that a specific human fallibility will be manifested
Mitigating Conditions	System factors that reduce the probability that a specific human fallibility will affect task performance, or that reduce the performance decrement.

The second phase of the performance analysis presents users with a list of necessary conditions (i.e. system factors which must be present in order for a specific human fallibility to be manifested), and prompts users to identify the necessary conditions that are present during the target task. If the necessary condition for a human fallibility is present, then it is possible for the human fallibility to manifest itself during the target task, potentially negatively impacting system performance. If the necessary condition for a human fallibility is not present during the target task, that fallibility is excluded from future analysis. Phase two further focuses the scope of the analysis on human fallibilities that are possible during the target task.

Phase Three: Error identification and remediation

The third phase of the performance analysis returns information to the user regarding possible human fallibilities and the human factors guidelines and considerations for each potential fallibility. Human factors considerations provide the analysts with information regarding factors that influence the probability, severity, and detectability of potential fallibilities. This includes information regarding the contributing, mitigating, and preventative conditions associated with each fallibility.

The guidelines are based on human factors principles, design rules, and heuristics. Guidelines provide the analyst with information necessary to redesign the task, train operators, and implement countermeasures and safeguards. During the third analysis phase users also have the opportunity to specify the ways potential human fallibilities may be manifested in the target system, and to add notation to each guideline regarding their concerns and insights specific to the task being analyzed. The human factors information provided and the ability to add notation supports the development of information-based remediation strategies.

Methodology Summary

HFIRM is a cause-oriented methodology that focuses on addressing the underlying conceptual and contextual causes of human error. This methodology facilitates the identification of human fallibilities that may be manifested during task-oriented performance. The analysis tool also supports the remediation of potential errors by providing analysts with the human factors information relevant to preventing errors and/or mitigating adverse effects.

HFIRM consists of three phases. The focuses of the first and second phases correspond roughly to the conceptual and contextual levels of human error articulated by Reason (1987). The third phase provides information crucial to the remediation of the conceptual, contextual, and behavior levels of human error. These phases are illustrated in Table 9.

Table 9: Human Performance Analysis Structure

Analysis Phase	**Error level considered**	**Purpose & Function**
One	Conceptual	• Identify the human information processing stages employed during the target task • Narrow the analysis to the human fallibilities that are possible during the human information processing stages selected
Two	Conceptual Contextual	• Determine which necessary conditions are present during the target task • Narrow the analysis to the human fallibilities that are associated with the necessary conditions that are present
Three	Conceptual Contextual Behavioral	• Provide the analysts with the human factors information necessary to determine the probability, severity, and detectability of potential fallibilities, errors and adverse events • Provide human factors principles, design rules, and heuristics needed to redesign the task, train operators, and implement countermeasures and safeguards • Support analysts in developing information-driven remediation strategies

The methodology supports the iterative elimination of human fallibilities that are not relevant to the target task. Analysts are then presented with a list of human fallibilities that are possible during the task, and the necessary information to determine how to appropriately intervene in order to support optimal system performance. The filtering process is illustrated in Figure 3.

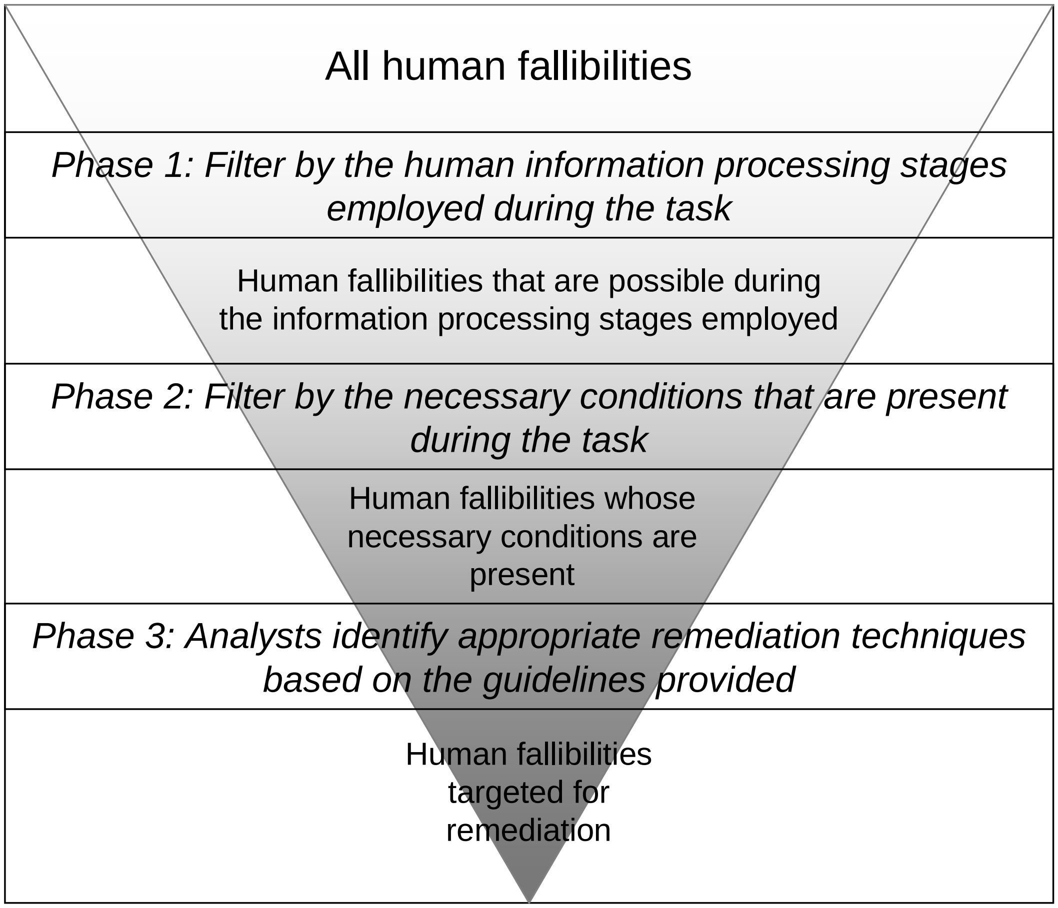


Figure 3: The HFIRM iterative filtering strategy

It is possible for human factors experts to apply HFIRM as a stand-alone analysis technique by drawing on their memory of the conceptual and contextual variables that influence the probability that a human fallibility will be manifested during a task. However, applying HFIRM in such an ad-hoc fashion relies heavily on the expertise and memory of the analyst. Given the quantity and complexity of the human performance information that needs to be considered for thorough analyses, ad-hoc application of the methodology is likely to result in inconsistent and inaccurate results.

In order to achieve the methodology goals defined earlier in the chapter, the methodology needs to be integrated with a mechanism that supports the primary functions of the HFIRM prototype. Specifically, the methodology needs to draw information from a knowledge source that defines relationships between human information processing stages, human fallibilities, necessary conditions for fallibilities to be manifested, and relevant human factors guidelines and considerations. In order to support Phases 1 and 2 of the analysis, HFIRM needs to be able to elicit specific information from the analysts regarding conceptual and contextual human and system factors in order to identify human fallibilities that may be manifested during the target task. During Phase 3, the analysis tool needs to be able to identify and return relevant human factors guidelines for each potential human fallibility identified during the first two phases. These guidelines must contain the human factors information necessary to identify potential errors, potential effects on system performance, and appropriate remediation strategies. Additionally, the analysis tool needs to provide analysts with the opportunity to enter notation for each guideline.

The appropriate tool to support the Human Fallibility Identification and Remediation Methodology (HFIRM) is a database. The database is a powerful data-sharing technology that has the capability to support the information storing and sharing functions required by the methodology. Integrating HFIRM with a database promotes the reliable implementation of the methodology. The development of the Human Fallibility Database is discussed in the next section.

Database Development

This section defines the database goals, describes the development of the ontology that provides the theoretical foundation of the database, and reviews the process used to design and populate the database. This chapter closes with a description of the functions and features of the resulting MS Access database and a tutorial for its implementation.

Database Goals

The purpose of the database is to support the function of Human Fallibility Identification and Remediation Methodology (HFIRM) and ultimately the fulfillment of the research objectives defined earlier in this chapter. In order to accomplish this, the database functionality must be aligned with the specific capabilities and characteristics of the methodology that were articulated in the research goals.

The following database goals specify the capabilities needed to support the achievement of the overarching objectives. The goals were defined by identifying the information storing and sharing functions that the database needs to provide in order to fully support the methodological procedure. Additionally, these goals document resource allocation decisions made by the researcher with expert guidance in order to support the achievement of the research objectives.

The goals of the database are as follows:

1. The human performance database will capture relevant information from *Engineering Psychology and Human Performance, 3rd Edition* (Wickens and Hollands, 2000). No new research into human performance will be conducted.
2. The database will identify meaningful associations between human information processing stages, human fallibilities, system variables, and relevant human factors principles and guidelines.
3. Forms and queries will be designed to guide analysts through an information-driven fallibility analysis of a target task.
4. The database will be structured for flexible use, allowing analysts to choose the scope of the analysis that they conduct.
5. The database will have the capability to return information to analysts regarding potential human fallibilities and the human factors guidelines relevant to preventing, reducing the probability of, and/or mitigating the effects of these error tendencies.
6. Only discrete relationships will be captured in the database. The framework will not include the capability to assess the relative probability, consequence severity, or detectability of potential negative system outcomes.
7. The software interface will be developed to a functioning level. Enhancements that have the potential to increase the sophistication, flexibility, and usability of the tool will be identified but not implemented.

Structural Development

This section describes the process used to develop the structure of the foundational ontology as well as the database structure.

The purpose of the Human Fallibility Database is to store and provide access to human factors information that supports the three-phase HFIRM outlined in the Methodology development section. This database is the mechanism through which data is stored and accessed in order to support the informational needs of HFIRM. In order to fulfill this purpose the information in the database must contain the information needed to perform the analysis, and it must be structured in a way that makes that information accessible to analysts using HFIRM. This structure was established through the development of a Human Fallibility Ontology which formally represents the concepts, attributes, and relationships within the HFIRM universe of discourse. The HFIRM universe of discourse is the human performance information necessary to identify the conceptual mechanisms that lead to human fallibilities, the contextual variables that influence the probability that human fallibilities will be manifested, and appropriate remediation techniques.

The architectural foundation of the database is an ontology that formally represents the concepts, attributes, and relationships within the HFIRM domain of interest. By formalizing the scope and the vocabulary of HFIRM, the ontology constrains the meaning of terms and enables consistent interpretation of the data. The development of the concepts, attributes, and relationships within the HFIRM universe of discourse is described in the next three sections.

Concept Development

The Human Fallibility Ontology was developed to support the objectives of the Human Fallibility Identification and Remediation Methodology (HFIRM). The concepts within this ontology must define the key elements within the universe of discourse encompassed by the methodology. This section defines the key concepts that support each phase of the methodology.

The fundamental strategy of the analysis is to improve human performance by supporting the identification of potential human fallibilities, which may precipitate human errors and cause negative consequences if left unchecked. The central ontological concept is therefore the Human Fallibility. In order to support the efficiency goal for the human performance analysis human fallibilities are organized by general categories. The resulting ontological concept is Human Fallibility Categories. Each Human Fallibility Category has specific criteria for membership and subsumes the multiple Human Fallibilities that meet these criteria.

The first phase of the analysis requires the consideration of the conceptual level of human error. The psychological roots of human error tendencies are expressed in the ontology as Human Information Processing Stages. The second phase of the analysis addresses contextual variables that influence the probability that fallibilities will be manifested. Specifically, phase two identifies the presence of conditions that are necessary for a fallibility to manifest itself during the target task. System variables that must be present during the target task in order for a fallibility to be manifested are represented in the ontology as the Necessary Conditions concept.

The objective of the third phase of the analysis is remediation of the potential human fallibilities and resulting adverse events. This phase provides human factors principles, consideration, and guidelines relevant to understanding, mitigating, and preventing the potential human error tendencies and their adverse effects. Information required for the Error Identification and Remediation phase is represented in the ontology as Guidelines. The concepts defined in the ontology are therefore Human Information Processing Stages, Human Fallibility Categories, Human Fallibilities, Necessary Conditions, and Human Factors Guidelines. These concepts are described in Table 10.

Table 10: Ontology concepts and descriptions

Ontology concept	Descriptions
Human Fallibility Categories	General categories of human fallibilities
Human Fallibilities	Human error tendencies
Human Information Processing Stages	The cognitive domains in which human error tendencies originate
Necessary Conditions	Characteristics of the task, operator, or environment which must be present in order for a fallibility to be manifested during a task
Human Factors Guidelines	Human factors principles and design rules regarding factors that influence the probability, severity, and detectability of potential fallibilities, as well as the contributing, mitigating, and preventative conditions for each potential human fallibility. Guidelines provide the analyst with information necessary to develop an informed remediation strategy.

The ontology defines and organizes the human factors information necessary to perform the three-phased Human Fallibility Identification and Remediation Methodology (HFIRM) described in the Methodology development section. Each concept in the ontology supports one or more phases of the HFIRM. The ontology concepts involved in each phase of the HFIRM are represented in Table 11.

Table 11: HFIRM phases and supporting ontological concepts

Analysis Phase	Error level considered	Supporting ontological concepts
One	Conceptual	• Human Information Processing Stages • Human Fallibility Categories
Two	Conceptual Contextual	• Necessary Conditions • Human Fallibility Categories • Human Fallibilities
Three	Conceptual Contextual Behavioral	• Guidelines • Human Fallibilities

The concepts described above establish the fundamental structure and scope of the Human Fallibility Ontology. The next step in the development of the ontology is to define these concepts by assigning attributes to them. Attributes capture relevant information about concepts and characterize the logical connections that exist between concepts. The development of the attributes within the Human Fallibility Ontology is described in the next section.

Attribute Development

General ontological structure dictates that each concept be assigned one or more attributes which define properties and characteristics of the object. During the development of the Human Fallibility Ontology, attributes were created to provide information that supports the fulfillment of the analysis and database goals. When appropriate, reference pages were included in order to identify the page from *Engineering Psychology and Human Performance, 3rd Edition* (Wickens and Hollands, 2000) where the object information was found. One attribute in each table serves as the primary key. Primary keys are unique identifiers that allow distinct relationships between table objects to be defined. Concepts and their defining attributes are presented in Table 12.

Table 12: Human Performance Ontology concepts, definitions, and attributes

Ontology concept	Definition	Attributes
Human Fallibility Categories	General categories of human fallibilities	Cat_ID (Primary Key) Name Definition W&H reference page
Human Fallibilities	Human error tendencies	HF_ID (Primary key) Name Definition W&H reference page
Human Information Processing Stages	The cognitive domains in which human error tendencies originate	HIPS_ID (Primary key) Name Definition Error Error Definition
Necessary Conditions	Characteristics of the task, operator, or environment which must be present in order for a fallibility to be manifested during a task	NC_ID (Primary key) Description
Human Factors Guidelines	Human factors principles and design rules regarding factors that influence the probability, severity, and detectability of potential fallibilities, as well as the contributing, mitigating, and preventative conditions for each potential human fallibility. Guidelines provide the analyst with information necessary to develop an informed remediation strategy.	Guide_ID (Primary key) Guideline

Relationship Development

In addition to identifying the concepts in the universe of discourse and their defining attributes, the ontology schema also describes the relationships between concepts. Ontology relationships are represented as verb phrases that describe the association or effect of one concept to another. For example, Human Fallibility Categories classify Human Fallibilities into subsets by criteria. Therefore, the relationship between Human Fallibility Categories and Human Fallibilities is one of subsumption, i.e. Human Fallibility Categories “subsume” Human Fallibilities. Human Fallibility Categories and Human Fallibilities are possible during specific human information processing stages. Therefore, instances of the Human Fallibility entity may have an “originate in” relationship with instances of the Human Information Processing Stages concept. Necessary conditions must be present during the task in order for specific human fallibility categories and human fallibilities to be manifested. Necessary Conditions therefore “make possible Human Fallibility Categories and Human Fallibilities. Relevant guidelines “provide information regarding” potential Human Fallibilities. The relationships between ontology concepts and their attributes are illustrated in Figure 4.

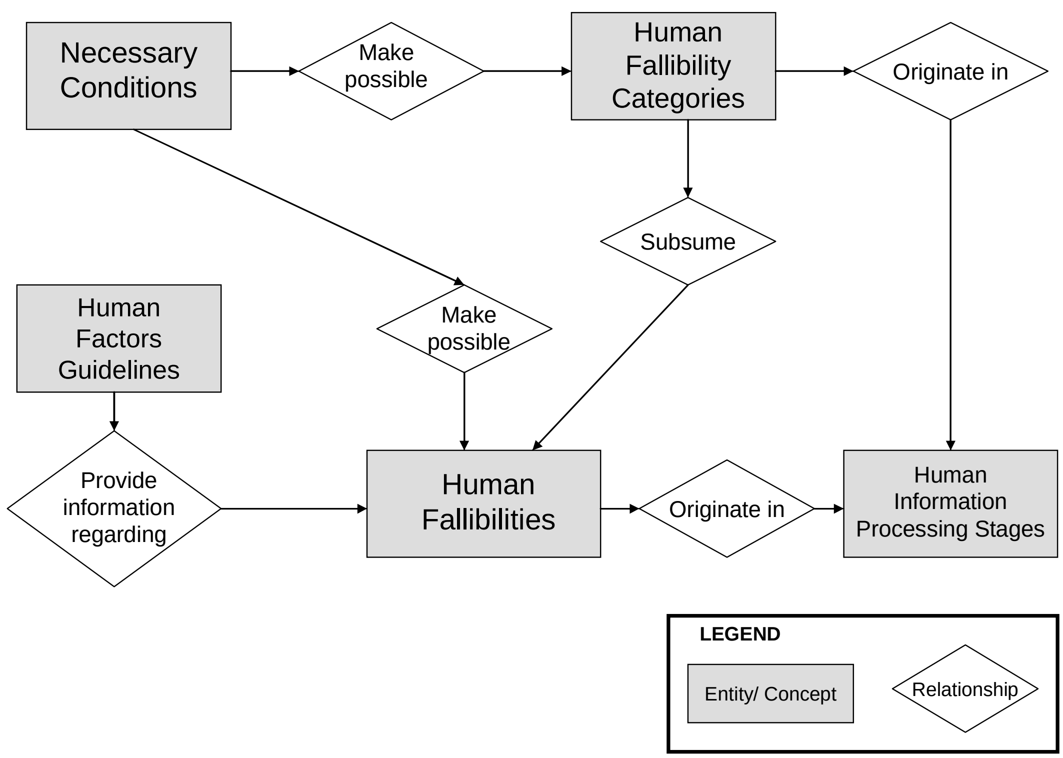


Figure 4: Human Performance Ontology entity-relationship diagram

Database Design

The ontology provides the architectural foundation for the database by defining the concepts, attributes, and relationships in the domain of interest. The database is the mechanism through which instances of information described conceptually by the ontology are stored, accessed, shared, and manipulated. The human performance database is a relational database that was developed in MS Access. Each of the concepts defined by the ontology is represented in a separate table in the database. The database entity names are HF_Categories, Human_Fallibility, HIPS, Necessary_Conditions, and Guidelines. The associations between the phases of the Human Performance Analysis, the ontology concepts, and the database concepts are represented in Table 13.

Table 13: Human Performance Analysis phases, support ontological concepts, and database associations

Analysis Phase	**Error level/s considered**	**Supporting ontological concepts**	**Database table names**
One	Conceptual	• Human Information Processing Stages • Human Fallibility Categories	• HIPS • HF_Categories
Two	Conceptual Contextual	• Necessary Conditions • Human Fallibility Categories • Human Fallibilities	• Necessary_Conditions • HF_Categories • HumanFallibility
Three	Conceptual, Contextual, Behavioral	• Human Factors Guidelines • Human Fallibilities	• Guidelines • HumanFallibility

All of the relationships classified by the ontology are “many-to-many,” meaning that an entry in Table A may have many linked relationships to an entry in Table B, and vice versa. For example, the Sensory Registration entry in the Human Information Processing Stage table may link to numerous entries in the Human Fallibilities table, indicating that many different human fallibilities may be manifested during Sensory Registration. Additionally, an entry in the Human Fallibilities table may link to several human information processing stages, indicating that the human fallibility may be manifested in multiple information processing stages. Database relationships are defined in link (i.e. tie) tables. Table

14 presents the ontological definitions of database entity relationships and the associated tie table.

Table 14: Human Performance database entity relationships and tie tables

Entity A	Relationship	Entity B	Tie table name
HF_Categories	Subsume	HumanFallibility	Cat_HF_Tie
HF_Categories	Originate in	HIPS	Cat_HIPS_Tie
HumanFallibility	Originate in	HIPS	HIPS_HF_Tie
Necessary_Conditions	Make possible	HF_Categories	Cat_NC_Tie
Necessary_Conditions	Make possible	HumanFallibility	NC_HF_Tie
Guidelines	Provide information regarding	HumanFallibility	HF_Guideline_Tie

Figure 5 illustrates database concepts, their attributes, and the structure of their relationships. The architectural foundation of the database is the ontological structure.

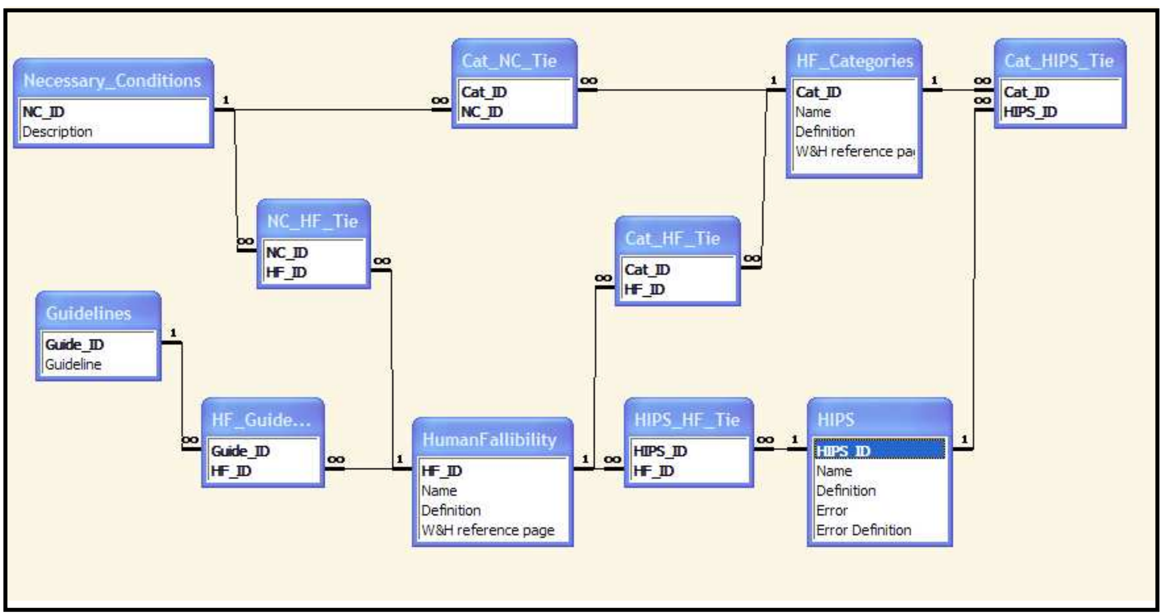


Figure 5: Human Fallibility Database entity-relationship diagram

Content Development

This section describes the process employed to translate information in *Engineering Psychology and Human Performance*, 3rd *Edition* (Wickens and

Hollands, 2000) into database content, the method used to populate the database, and examples of the resulting table entries.

The *Engineering Psychology and Human Performance* text was chosen as an appropriate source for the database content because it is a reliable resource for a wide range of human performance information. All 550 pages of the text were analyzed and human information processing stages, human fallibilities, system variables, and human factors principles and guidelines were identified. Pertinent information was paraphrased, reworded in order to be consistent in sense and syntax, and entered into the Human Fallibility Database. The procedure used to enter information into the database is described in the next section.

Database Population

After the database content had been extracted from *Engineering Psychology and Human Performance*, the following process was used to enter the content into the database.

1. Information was added to the primary tables in the following order:
    - HF categories
    - Human Fallibilities
    - Necessary Conditions
    - Guidelines
    - The HIPS table was fully populated before the remainder of the database content.

2. Information was added to the relationship tie tables in the following order:
    - Cat_HF_Tie
    - HIPS_HF_Tie
    - Cat_HIPS_Tie
    - Cat_NC_Tie
    - NC_HF_Tie
    - HF_Guide_Tie

When all of the relevant information from the *Engineering Psychology and Human Performance* text had been coded, the database contained 1045 objects (i.e. instances of concepts) and 1805 instances of relationships. These statistics are presented in Table 15.

Table 15: Human Performance Database statistics

Database concepts	**Number of Objects**
HF categories	18
Human Fallibilities	257
Human Information Processing Stages	7
Necessary Conditions	113
Guidelines	650
Total # of Objects	**1045**
Tie tables	**Number of Relationships**
Cat_HF_Tie	251
HIPS_HF_Tie	508
Cat_HIPS_Tie	74
Cat_NC_Tie	18
NC_HF_Tie	248
HF_Guide_Tie	706
Total # of Relationships	**1805**
GRAND TOTAL	**2850**

HFIRM prototype

The previous sections in this chapter described the development of the analytical framework and the development of the Human Fallibility Database structure and content. This section describes the MS Access forms and queries that were developed to guide users through the methodology while drawing relevant information from the Human Fallibility Database during each step of the methodology. Additionally, this section provides a demonstration of the HFIRM prototype by applying the methodology to a real-world task.

Form and query progression

This section describes the forms and queries that were developed to operationalize the HFIRM prototype. Each form and its associated queries support a phase of the analysis methodology or contribute to the fulfillment of the research goals. This section describes the functions and features of the MS Access Human Fallibility Database forms and queries.

The general strategy of the analysis methodology is to identify potential human fallibilities by soliciting specific information from analysts regarding human information processing stages and system factors. The relationships between the database concepts are captured in MS Access tables. The forms and queries present relevant information to the analysts during each step of the analysis procedure. When possible, descriptions or definitions are included to provide users with background information, additional visibility to the underlying causes of error, and insight into system interactions and interdependencies.

MS Access forms prompt analysts to select relevant information from list boxes. Based on the selections made by the analysts, the underlying Human Fallibility Database is queried. Query results are fed into the next form and displayed to users. The information provided by users during each step of the analysis process supports the iterative elimination of irrelevant fallibilities, progressively narrowing the scope of the analysis to only those fallibilities which can be manifested during the target task. In the final step of the analysis users have the opportunity to enter notation for each guideline associated with a potential human fallibility. This section details the progression of the methodology through each of its three phases and the function of each form and query.

Introduction

- The first MS Access form displayed to analysts contains introductory information including an overview of the purpose of the analysis, the resource required to conduct the analysis, and the steps in the analysis process. The introductory form is presented in Figure 6.

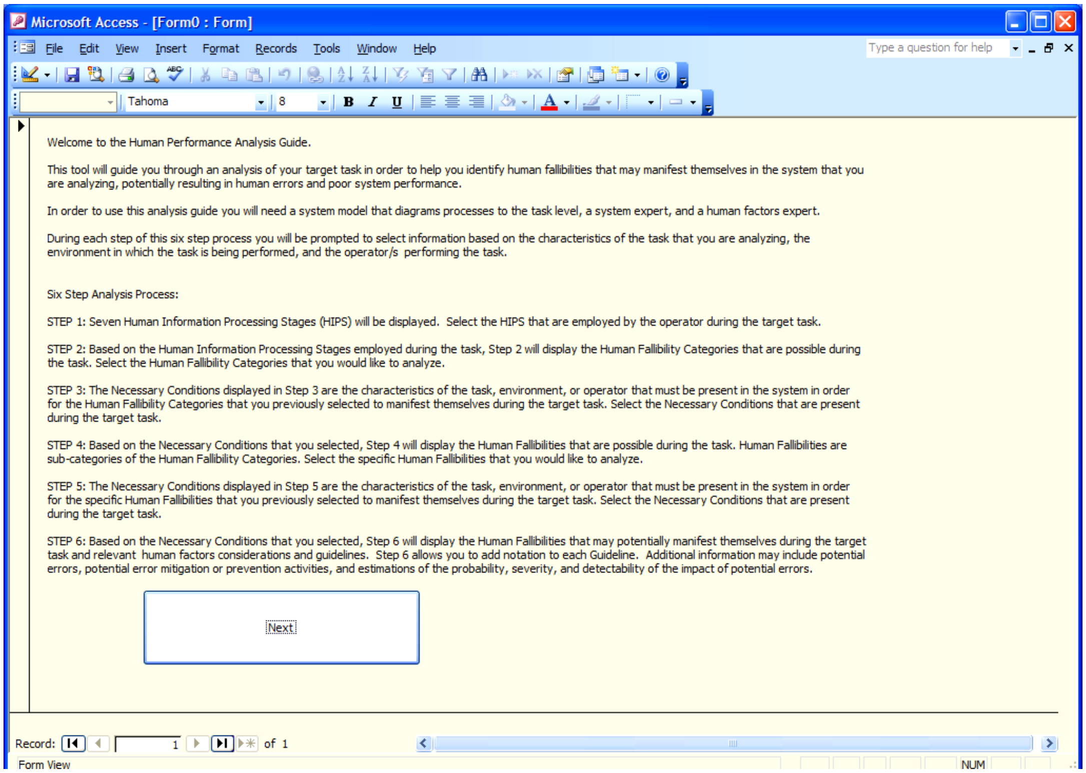


Figure 6: The first form contains introductory information

Phase 1

Phase 1 addresses the conceptual level of human error. At the end of Phase 1, the methodology has narrowed the analysis to consider only the Human Fallibility Categories that can be manifested during the Human Information Processing Stages employed during the target task.

- Step 1 displays the seven Human Information Processing Stages in a list box, and prompts users to choose the ones that are employed during the target task. Step 1 is displayed in Figure 7.
- QueryHIPS_HF queries the Cat_HIPS_Tie table for Human Fallibility Categories associated with the selected Human Information Processing Stages. The query returns the Human Fallibilities Categories that can be manifested during the selected Human Information Processing Stages to Step 2.

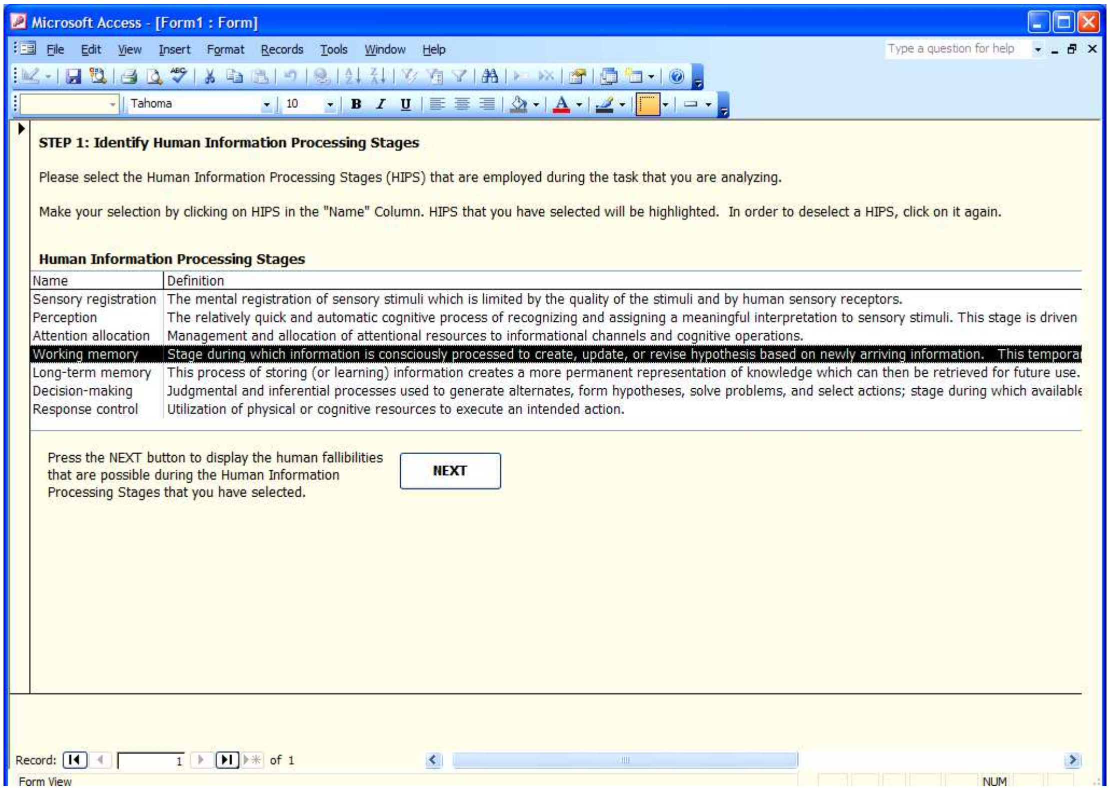


Figure 7: Step 1 displays Human Information Processing Stages

Phase 2

Phase 2 addresses the contextual level of human error by considering the situational factors that influence the probability that a human fallibility will be manifested. By the end of Phase 2, the methodology has narrowed the analysis to consider only those human fallibilities whose Necessary Conditions are present in the system. In order to increase the efficiency of the elimination process, Phase 2 prompts users to first identify the Necessary Conditions for general Human Fallibility Categories. Users are then asked to identify the Necessary Conditions for the specific Human Fallibilities within the possible Human Fallibility Categories. Step 2 and Step 4 increase the flexibility of the analysis by allowed advanced users to select specific fallibilities in order to conduct a more targeted analysis.

- Step 2 displays the Human Fallibility Categories returned by Query 1 in a list box, and prompts users to either check the "Select all" box for a complete analysis or to select only the human fallibilities of interest from the list box for a more targeted analysis. Form 2 is displayed in Figure 8.

- Query 2 queries the Cat_NC_Tie table for Necessary Conditions associated with the selected Human Fallibility Categories. The query returns the resulting Necessary Conditions to Step 3.

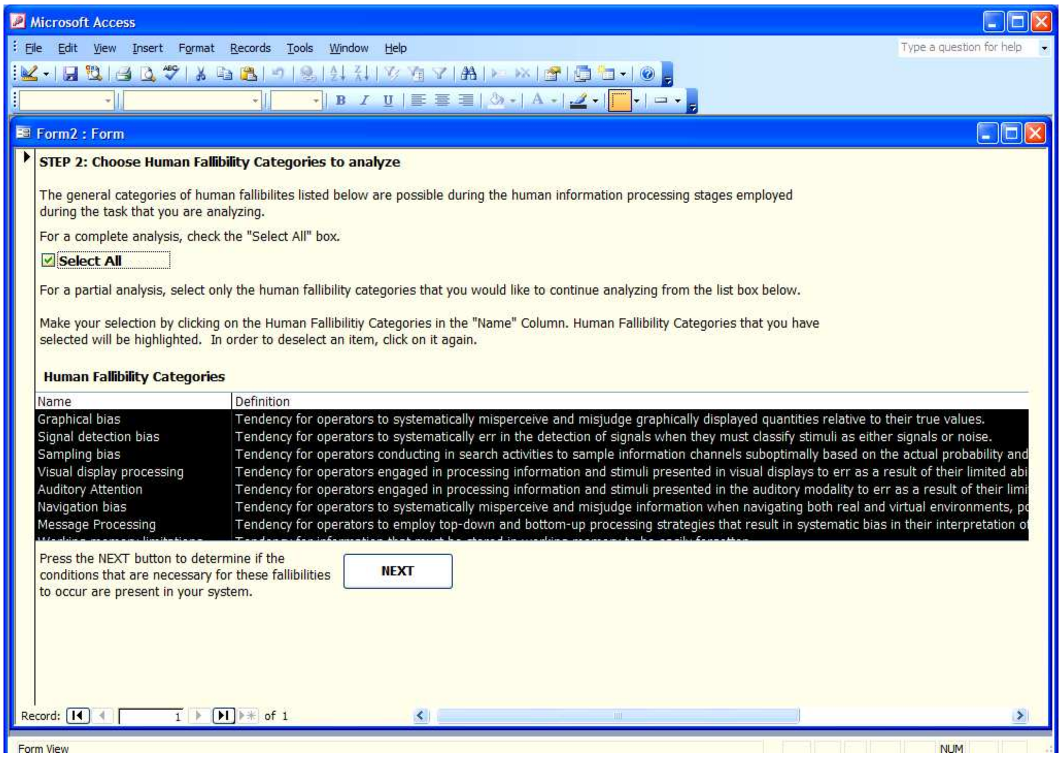


Figure 8: Step 2 displays possible Human Fallibility Categories

(Phase 2 continued)

- Step 3 displays the Necessary Conditions returned by Query 2, and prompts users to select the Necessary Conditions statements that are true for the target task from the list box. Step 3 is displayed in Figure 9.
- Query 3 queries the Cat_NC_Tie table for Human Fallibility Categories associated with the selected Necessary Conditions. The query returns the associated Human Fallibility Categories if and only if they are associated with at least one of the Human Information Processing Stages selected in Step 1.

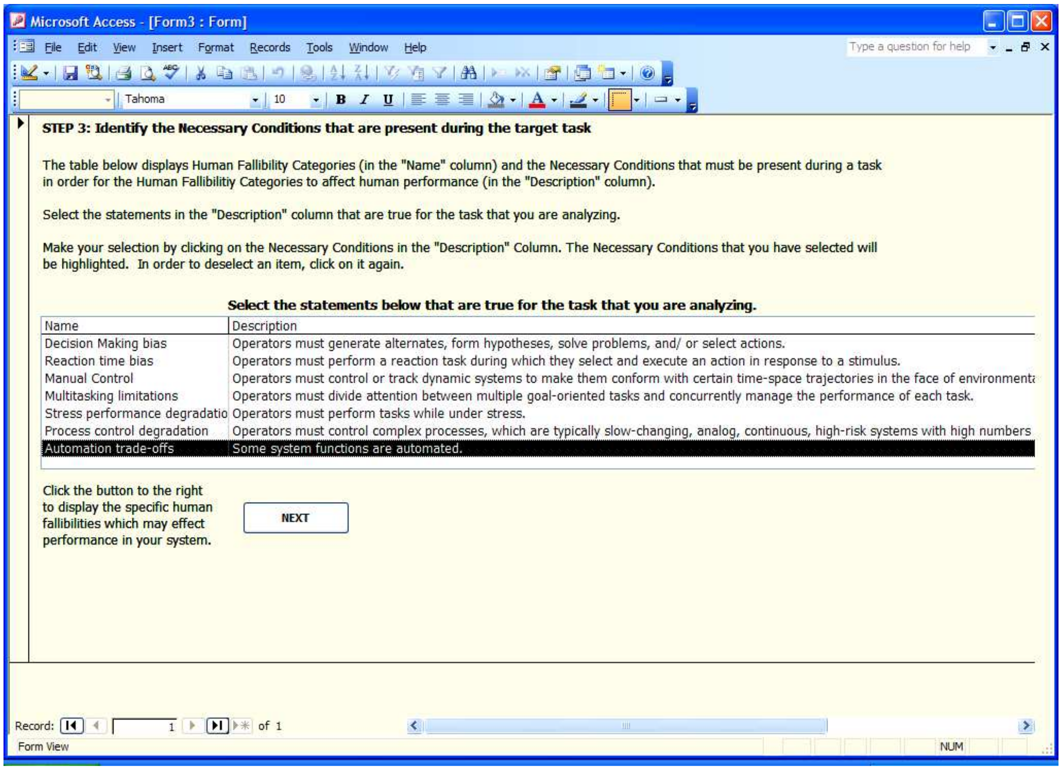


Figure 9: Step 3 displays the relevant Necessary Conditions

(Phase 2 continued)

- Step 4 displays the specific Human Fallibilities returned by Query 3, and prompts users to either check the “Select all” box for a complete analysis or to select only the fallibilities of interest from the list box for a more targeted analysis. Form 4 is displayed in Figure 10.
- Query 4 queries the NC_HF_Tie table for Necessary Conditions associated with the selected Human Fallibilities and returns the associated Necessary Conditions to Step 5.

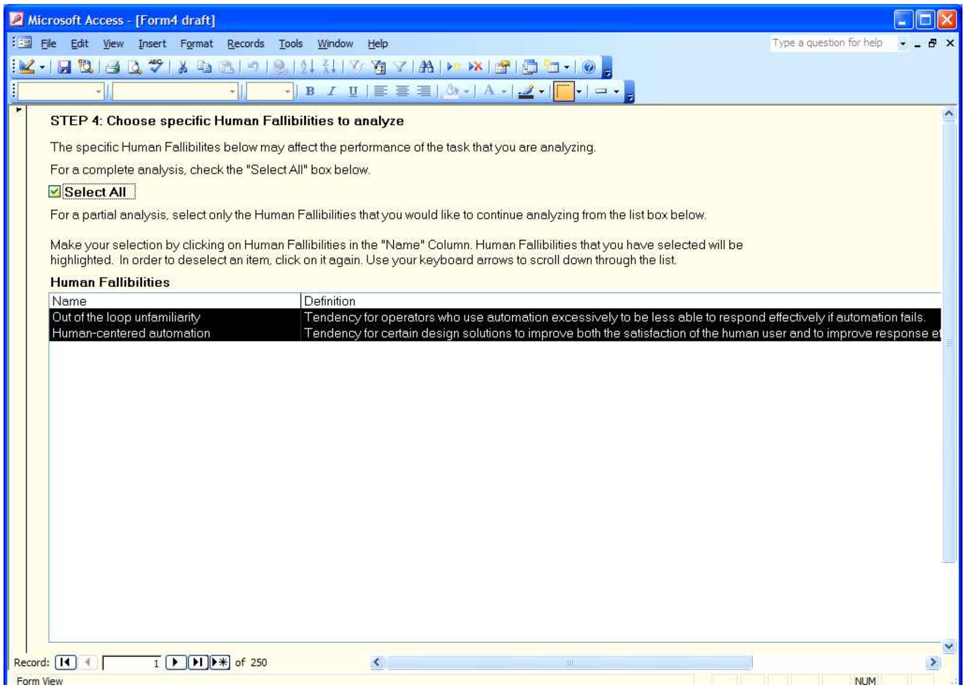


Figure 10: Step 4 displays potential specific Human Fallibilities

(Phase 2 continued)

- Step 5 displays the Necessary Conditions returned by Query 4 in a list box, and prompts users to select the Necessary Conditions statements that are true for the target task. Step 5 is displayed in Figure 11.
- Query 5 queries the NC_HF_tie table for Human Fallibilities associated with the selected Necessary Conditions. The query returns the name and description of the Human Fallibilities and the Guidelines associated with each Human Fallibility to Step 6.

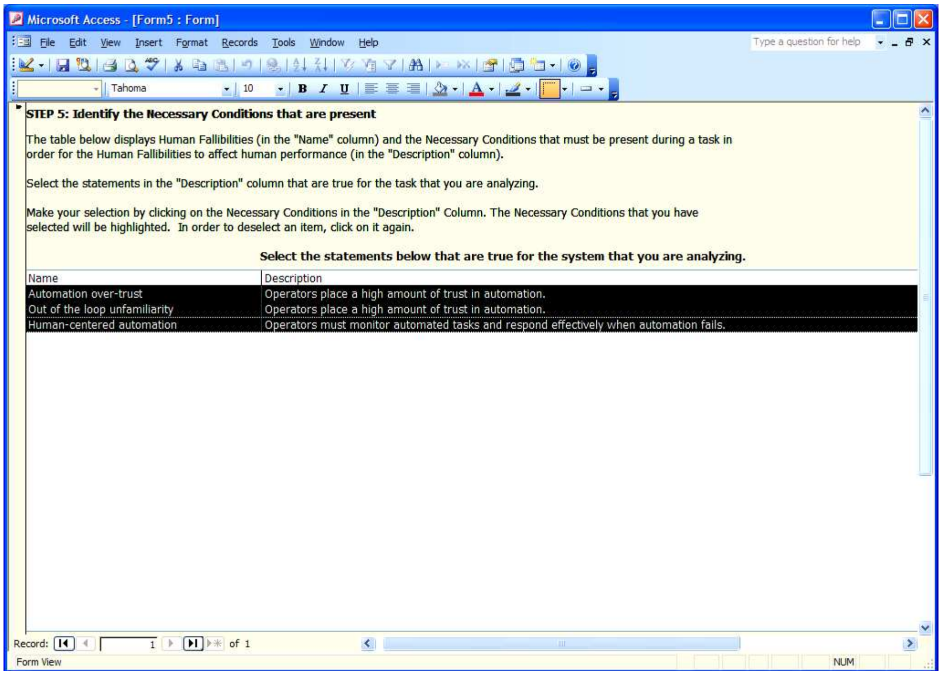


Figure 11: Step 5 displays the relevant Necessary Conditions

Phase 3

Phase 3 supports the identification of potential errors and the development of information-driven remediation strategies by providing users with a report that outlines the potential human fallibilities and human factors information relevant to determining how and if they may be manifested, and how to implement effective interventions. In order to support this process Phase 3 allows users to enter notation for each human factors guideline associated with a potential human fallibility.

- Step 6 displays a multiple page form. Each page displays a Human Fallibility returned by Query 5, its name, description, and one associated guideline. The form prompts the user to enter notation for each guideline as desired. Step 6 is displayed in Figure 12.
- Query 6 feeds the potential Human Fallibility names, definitions, associated guidelines, and user-entered notation into a MS Access report.

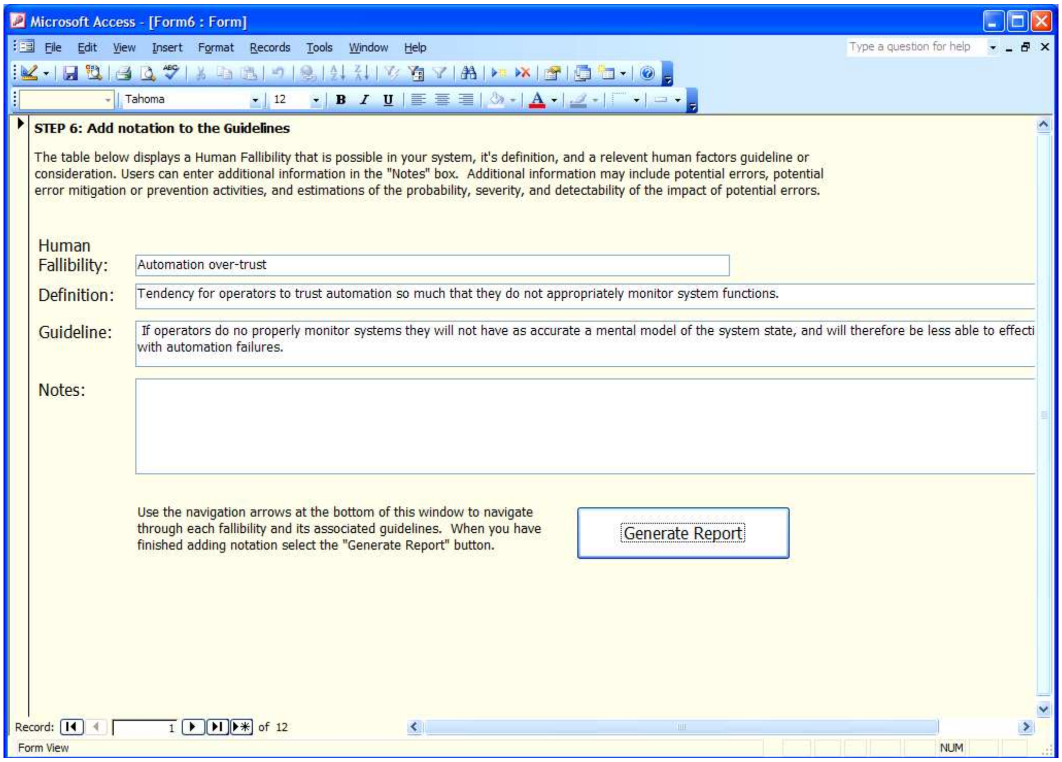


Figure 12: Step 6 provides analysts with an opportunity to enter Notes

(Phase 3 continued)

- The Final Report displays the names and definitions of potential Human Fallibilities, their associated guidelines, and the user-entered notation. The report is paginated and can be saved as a PDF file for future reference. The Final Report is displayed in Figure 13.

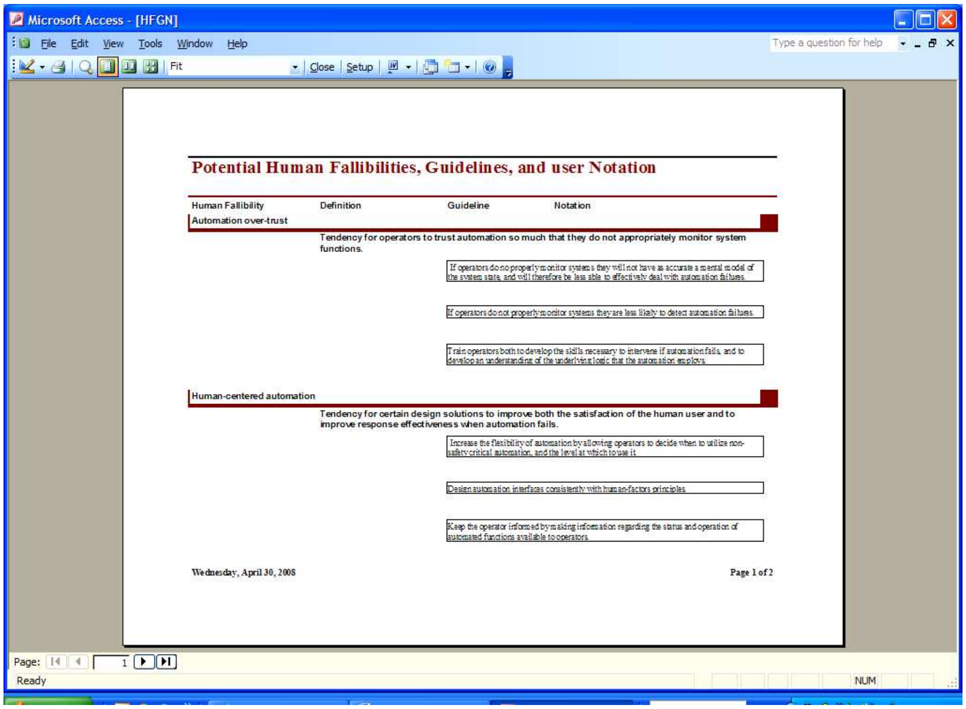


Figure 13: Final report

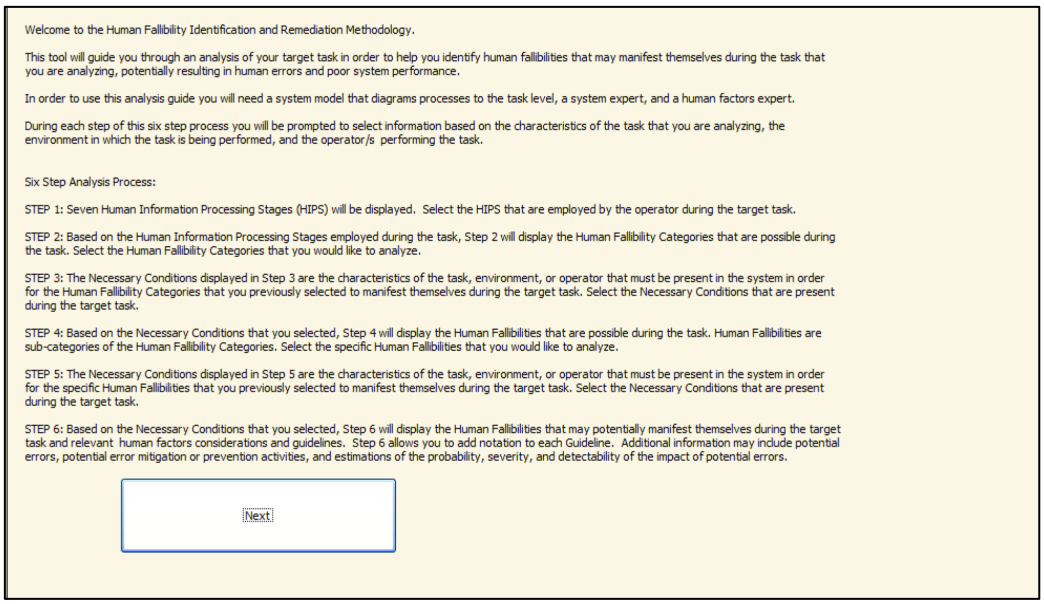
The outline provided above of the forms and queries that support the implementation of the HFIRM prototype illustrates the extent to which the methodology supports the systematic application of human factors theory. The next section provides a simple example to demonstrate the application of the methodology to a real-world task. A detailed user procedure for using the HFIRM prototype is provided in Appendix A.

HFIRM Example

The purpose of the HFIRM prototype is to support the prospective identification and remediation of potential human errors in complex real-world systems. This is accomplished by guiding users through a systematic methodology that draws from a database of human factors knowledge in order to provide analysts with information relevant to identifying human errors and developing appropriate intervention strategies.

The functions and capabilities of the HFIRM prototype are demonstrated below through application to a real-world task: monitoring vehicle speed while operating an automobile. Monitoring of system status is a common and important function that operators perform in many complex systems. This monitoring task is relatively simple, making it a good choice for demonstrating the practical value of the HFIRM prototype in an efficient manner. The purpose of this example is to demonstrate how HFIRM can be used to analyze a real-world task.

The first MS Access form in the HFIRM prototype provides an overview of the analysis methodology. This form displays regardless of the task being analyzed, and does not require any task specific information from the user. Figure 14 presents the introductory form (Form 0).


Welcome to the Human Fallibility Identification and Remediation Methodology.

This tool will guide you through an analysis of your target task in order to help you identify human fallibilities that may manifest themselves during the task that you are analyzing, potentially resulting in human errors and poor system performance.

In order to use this analysis guide you will need a system model that diagrams processes to the task level, a system expert, and a human factors expert.

During each step of this six step process you will be prompted to select information based on the characteristics of the task that you are analyzing, the environment in which the task is being performed, and the operator/s performing the task.

Six Step Analysis Process:

STEP 1: Seven Human Information Processing Stages (HIPS) will be displayed. Select the HIPS that are employed by the operator during the target task.

STEP 2: Based on the Human Information Processing Stages employed during the task, Step 2 will display the Human Fallibility Categories that are possible during the task. Select the Human Fallibility Categories that you would like to analyze.

STEP 3: The Necessary Conditions displayed in Step 3 are the characteristics of the task, environment, or operator that must be present in the system in order for the Human Fallibility Categories that you previously selected to manifest themselves during the target task. Select the Necessary Conditions that are present during the target task.

STEP 4: Based on the Necessary Conditions that you selected, Step 4 will display the Human Fallibilities that are possible during the task. Human Fallibilities are sub-categories of the Human Fallibility Categories. Select the specific Human Fallibilities that you would like to analyze.

STEP 5: The Necessary Conditions displayed in Step 5 are the characteristics of the task, environment, or operator that must be present in the system in order for the specific Human Fallibilities that you previously selected to manifest themselves during the target task. Select the Necessary Conditions that are present during the target task.

STEP 6: Based on the Necessary Conditions that you selected, Step 6 will display the Human Fallibilities that may potentially manifest themselves during the target task and relevant human factors considerations and guidelines. Step 6 allows you to add notation to each Guideline. Additional information may include potential errors, potential error mitigation or prevention activities, and estimations of the probability, severity, and detectability of the impact of potential errors.

Next

Figure14: The HFIRM prototype introductory form (Form 0)

After reading the introductory form and selecting the “Next” button, the first form that prompts users to enter information regarding the target task is displayed. Step 1 of the methodology prompts users to identify the Human Information Processing Stages employed during the task. The Human Information Processing Stages that are of central importance to the task of monitoring the speed of an automobile are Perception and Attention Allocation. Perception is critical because in order to effectively monitor speed operators must quickly recognize and assign meaning to the displayed speed, e.g. “65 mph is too fast,” “40 mph is too slow,” etc. Attention allocation is central to this task because operators must effectively manage their limited attentional resources to both monitor the speed of the automobile and perform the other tasks involved with operating an automobile. Step 1 of the analysis is displayed in Figure 15.

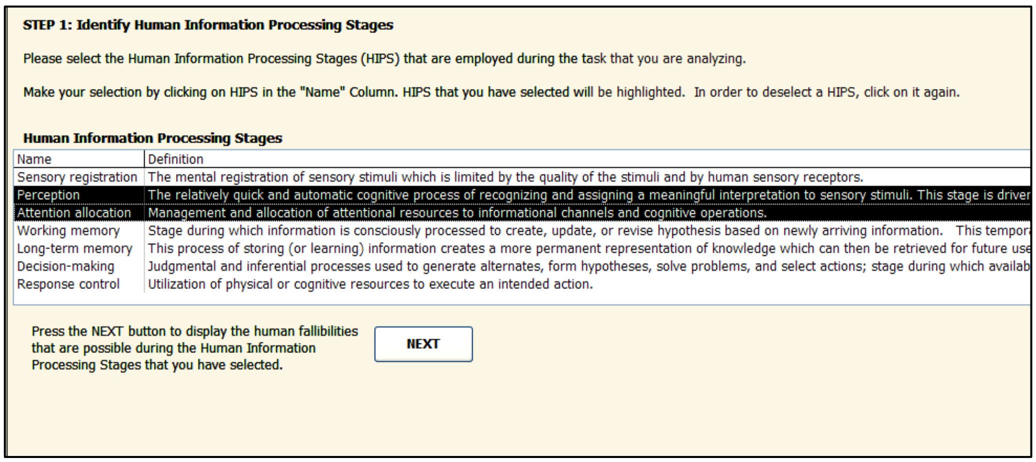


Figure 15: Step 1 prompts users to identify the primary Human Information Processing Stages employed during the target task

After users select the Human Information Processing Stages, “Perception” and “Attention allocation” and select the “Next” button, the Human Fallibility Database is queried based on these selections. The next form (Step 2) in the HFIRM prototype displays the Human Fallibility Categories that are possible during tasks that employ Perception and Attention allocation. This form is intended to provide users with additional flexibility regarding the comprehensiveness of the analysis that they perform. Step 2 of the methodology prompts users to choose only the potential Human Fallibility Categories that they would like to continue to analyze, or to “Select All” for a complete analysis. In order to perform a complete analysis of the “monitor speed” task users check the “Select All” box. Step 2 of the analysis is displayed in Figure 16.

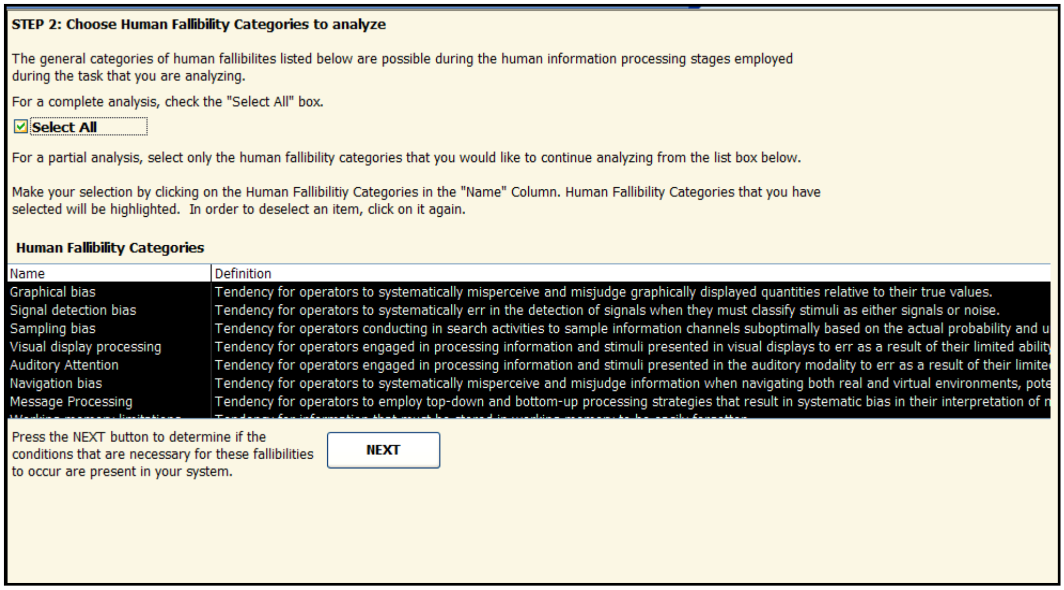


Figure 16: Step 2 provides users with the flexibility to choose the comprehensiveness of the analysis that they conduct

After users check the “Select All” box and select the “Next” button, the Human Fallibility Database is queried based on the Human Fallibility Category selections made by the user during Step 2. Step 3 displays the Necessary Conditions that must be present in order for the Human Fallibility Categories selected by the user during Step 2 to be manifested. Step 3 prompts users to select the statements in the list box that are true for the target task. These statements represent Necessary Conditions, which, if present, make it possible for specific human fallibilities to be manifested during the performance of the target task.

For the task of monitoring the speed of an automobile, two of the statements presented during Step 3 are true (see Figure 17). Operators monitor the speed of the automobile by reading the speedometer, therefore the statement, “Operators must interpret a display or graph” is true. Additionally, operators must focus their attention on the speedometer without being confused by the other displays on the dashboard and while continuing to perform the other tasks involved in operating an automobile. Therefore, the statement, “Operators must appropriately allocate attention to concurrently process or selectively attend to visual stimuli presented in displays" is also true. Both of the correct selections for Step 3 are highlighted in Figure 17.

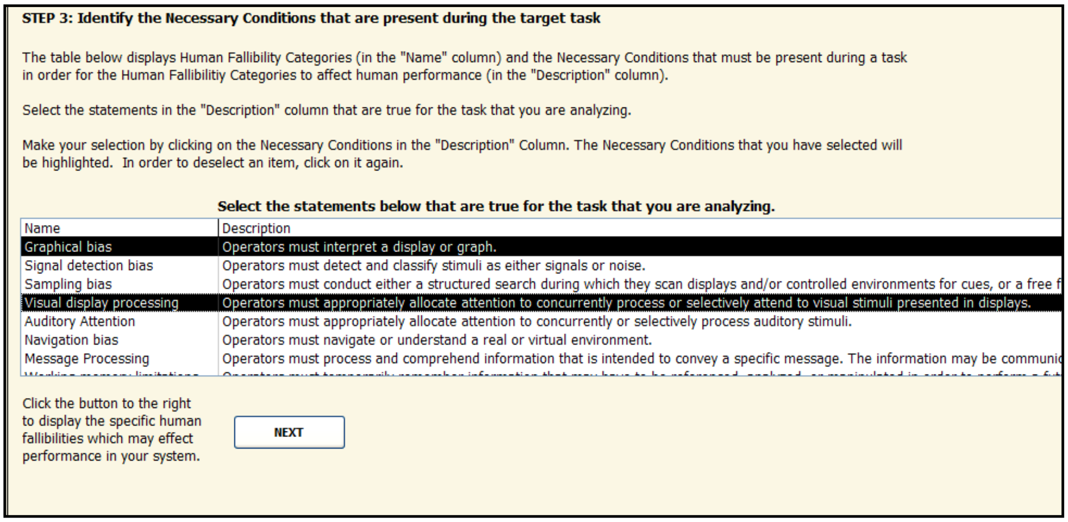


Figure 17: Step 3 prompts analysts to identify statements that are true regarding the target task

After selecting the statements that are true for the target task and selecting the "Next" button, users are directed to Step 4 in the analysis. Similar to Step 2, Step 4 provides users with additional flexibility regarding the comprehensiveness of the analysis that they conduct. In order to conduct a complete analysis users check the "Select All" box. Alternatively, advanced users can select individual human fallibilities to continue analyzing from the list box. This example demonstrates a complete analysis. Figure 18 displays Step 4 with the "Select All" box checked for a complete analysis.

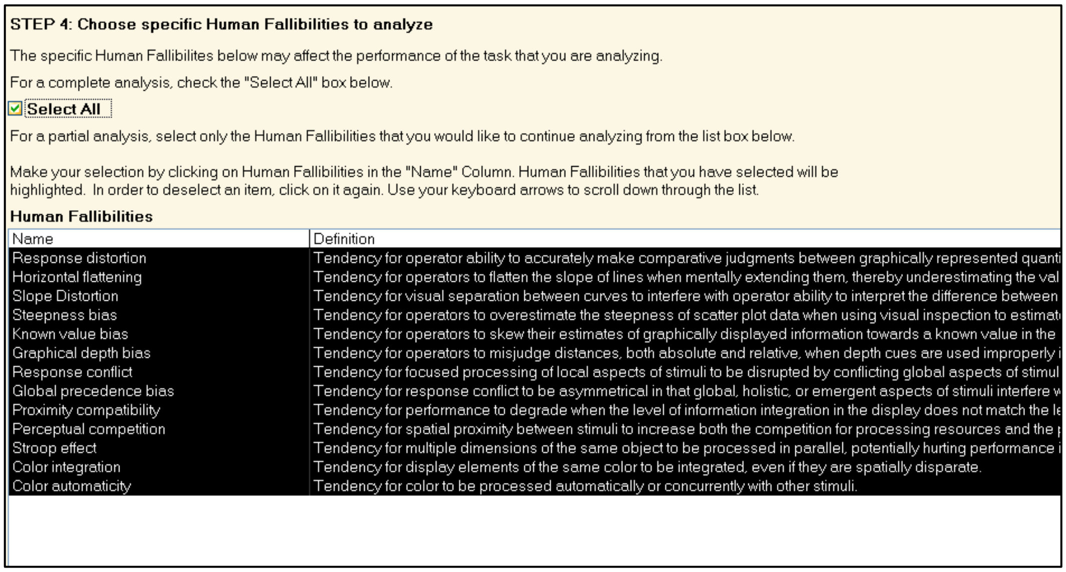


Figure 18: Step 4 provides users with the flexibility to choose the comprehensiveness of the analysis that they conduct

After checking the “Select All” box and selecting the “Next” button, the Human Fallibility Database is queried based on the specific Human Fallibility selections made by the user during Step 4. Step 5 displays the Necessary Conditions that must be present in order for the Human Fallibilities selected by the user during Step 4 to be manifested. Step 5 prompts users to select the statements in the list box that are true for the target task. These statements represent Necessary Conditions, which, if present, make it possible for specific human fallibilities to be manifested during the performance of the target task. For the task of monitoring the speed of an automobile, two of the statements presented in Step 5 are true (See Figure 19). Many speedometers use a pointer that does not reach to the speed labels, requiring operators to mentally extend the line made by the pointer to the speed labels. Therefore, the statement “Operators must mentally extend a line beyond the displayed range in order to determine if points (or line segments) lie along the same trend” is true. Additionally, how frequently and how carefully the operator checks the speedometer will be determined by the objectives of the task e.g. if maintaining a precise speed is critical, then operators will need to dedicate more attention to speed maintenance than if a larger range of speeds is acceptable.

Therefore the statement, “Operators must appropriately allocate attention to display information channels and stimuli based on task objectives” is also true. Figure 19 displays Step 5 with the appropriate Necessary Conditions selected.

STEP 5: Identify the Necessary Conditions that are present

The table below displays Human Fallibilities (in the "Name" column) and the Necessary Conditions that must be present during a task in order for the Human Fallibilities to affect human performance (in the "Description" column).

Select the statements in the "Description" column that are true for the task that you are analyzing.

Make your selection by clicking on the Necessary Conditions in the "Description" Column. The Necessary Conditions that you have selected will be highlighted. In order to deselect an item, click on it again.

Select the statements below that are true for the system that you are analyzing.

Name	Description
Response distortion	The task requires the operator to make relative judgments of graphically displayed perceptual continua (such as changes in
Horizontal flattening	Operators must mentally extend a line beyond the displayed range in order to determine if points (or line segments) lie along
Slope Distortion	The operator must estimate the difference between the slopes of separate curves.
Steepness bias	Operators must use visual inspection or estimation to fit a line to a scatter plot or to determine which values in a scatter plot
Known value bias	Operators must estimate the value of graphically displayed information of unspecified value when one or more graphical ele
Graphical depth bias	A two-dimensional display space is being used to create a three-dimensional representation of a physical system.
Response conflict	Operators must selectively attend to specific visual information channels presented within a display without being distracted.
Global precedence bias	Operators must selectively attend to specific visual information channels presented within a display without being distracted.
Local processing bias	Operators must selectively attend to specific visual information channels presented within a display without being distracted.
Proximity compatibility	Operators must appropriately allocate attention to display information channels and stimuli based on task objectives.
Perceptual competition	Operators must appropriately allocate attention to display information channels and stimuli based on task objectives.
Stroop effect	Operators must process multiple information channels in object displays which have been designed so that multiple stimuli h
Color stereotypes	Operators must process multiple information channels in color-coded displays.
Color integration	Operators must process multiple information channels in color-coded displays.
Color continuum ambiguity	Operators must process multiple information channels in color-coded displays.
Color automaticity	Operators must process multiple information channels in color-coded displays.

Figure 19: Step 5 prompts analysts to identify statements that are true regarding the target task

After users identify the statements in Step 5 that are true for the “monitor speed” task, the Human Fallibility Database is queried for Human Fallibilities associated with those Necessary Conditions. The Human Fallibilities returned by that query are presented to analysts in Step 6. The definitions of the Human Fallibilities and the human factors Guidelines associated with the Human Fallibilities are also returned. Step 6 requires the human factors expert and the system expert to cooperatively pool their knowledge to use the Human Fallibilities and Guidelines presented to identify potential system-specific human errors, impacts, and intervention strategies.

Step 6 presents analysts with a series of forms: one form for each guideline associated with a potential Human Fallibility. Analysts are given the opportunity to enter information regarding each guideline into the Notes field. Analysts may enter notations regarding potential errors that may occur if the fallibility is manifested, promising intervention strategies, or any other information that they want to document.

Figure 20 presents the first form in Step 6 for the analysis of the "monitor speed" task. Based on the potential Human Fallibility ("Horizontal flattening"), its definition, and the associated Guideline, one logical potential error that can be identified is that when reading the speedometer and mentally extending the line of the speed pointer to determine the indicated speed, operators may extend the line at an incorrect angle, causing them to misjudge the speed of the automobile. This potential error is captured in the Notes section in Figure 20.

The Guideline associated with the "Horizontal flattening" fallibility recommends including reference information in displays, potentially by adding tick marks to displays. This guideline can be employed for the "monitor speed" task by adding tick marks to the speedometer between the numerical speed labels. Another common-sense design intervention is to make the speed pointer longer so that it extends the full distance to the speed labels, eliminating the need for operators to mentally extend the line. This design intervention is captured in the notation box in Figure 20 along with the potential error previously identified.

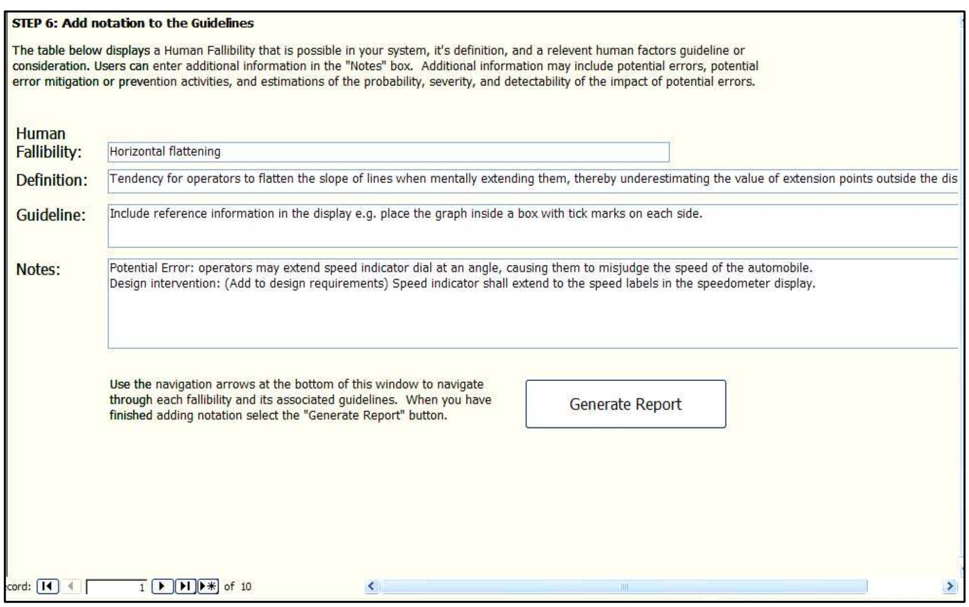


Figure 20: The Notes field in Step 6 allows analysts to enter notation for each guideline

Analysts navigate through the different forms presented in Step 6 using the arrows on the bottom left of the screen. The second form in Step 6 for this analysis of the “monitor speed” task is presented in Figure 21. Analysts use the information presented regarding the Human Fallibility (“Perceptual competition”), its definition, and the associated Guideline, in order to identify potential errors and remediation strategies. These potential errors and remediation strategies are entered in the Notes field, as illustrated in Figure 21.

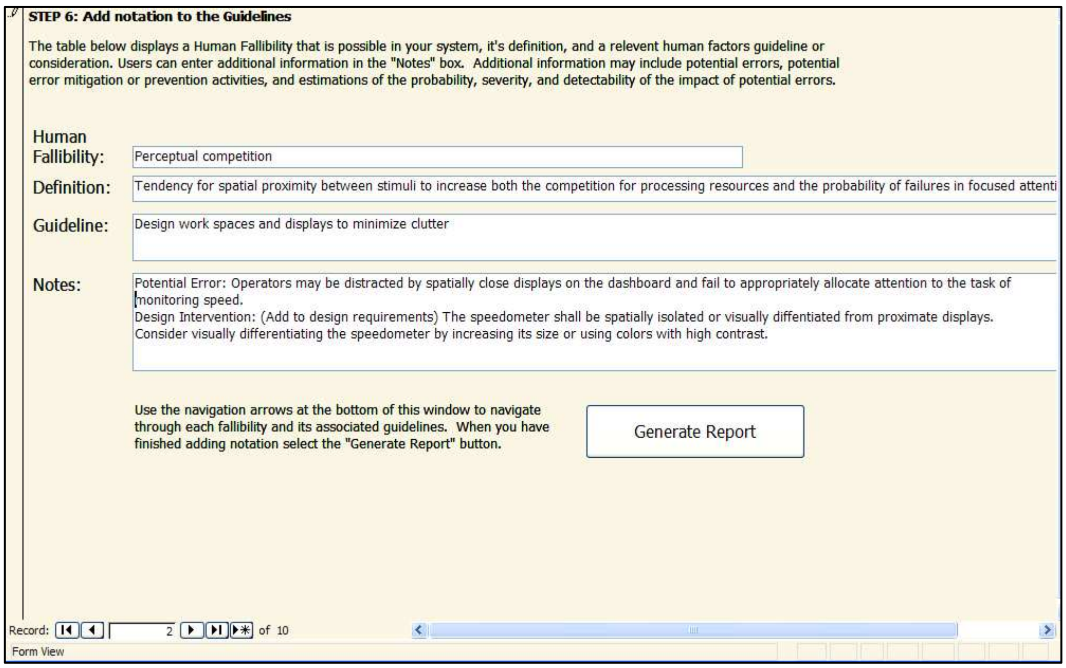


Figure 21: Step 6 may contain multiple forms, each of which presents a different guideline and allows analysts to enter Notes.

After the analysts navigate through all the forms in Step 6 and enter Notes the HFIRM prototype produces a report which can be saved as a PDF file. The report includes all the potential Human Fallibilities, their definitions, associated guidelines, and the notes entered by the analysts during Step 6. The first page of the report for this example analysis of the “Monitor speed” task is displayed in Figure 22.

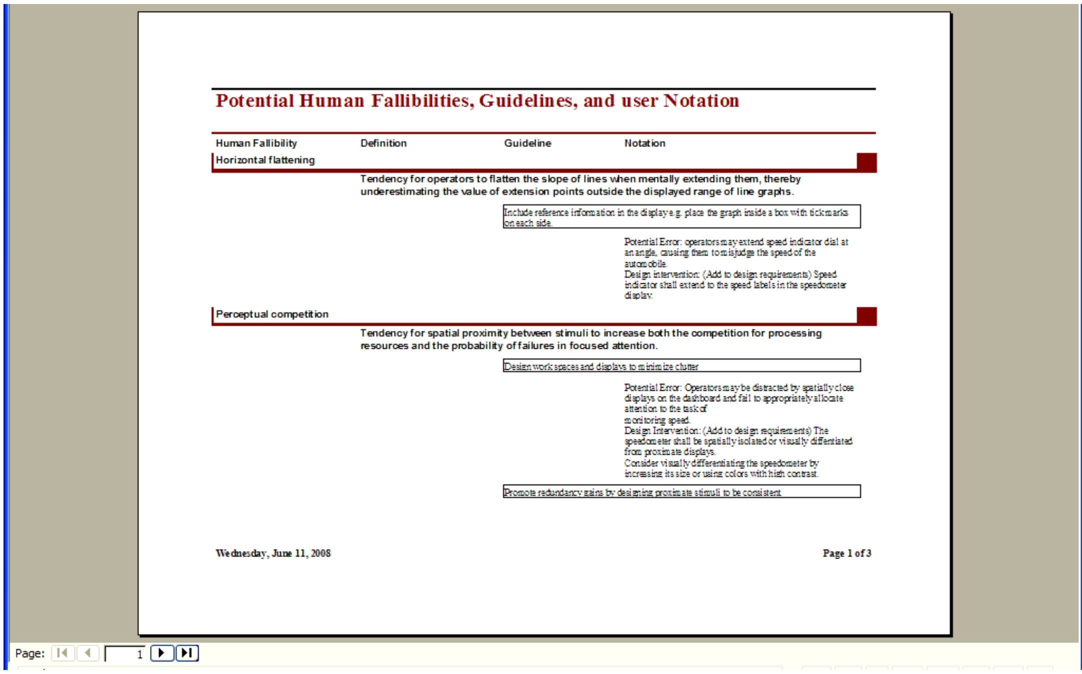


Figure 22: First page of the Final report for the “monitor speed” task analysis

The example above demonstrates how the HFIRM prototype guides analysts through an information-driven task analysis in order to support the identification and remediation of potential human errors. The targeted information that is presented to users during each stage of the analysis serves as a memory-aid and encourages the accurate and consistent examination of the target task. This methodology does not replace the need for expert judgment, but it does address the volume of information and the complexity of the relationships that need to be considered when conducting human error analyses. By integrating a cause oriented-methodology with the Human Fallibility Database the HFIRM prototype provides a systematic and theory-based method that promotes the practical application of human performance information to the analysis of complex human-machine systems.

The Methodology chapter described the objectives and associated goals of this research. This chapter also described the development of the three phases of the analysis methodology and the Human Fallibility Database. Finally, this chapter demonstrated the capabilities of the HFIRM prototype by analyzing a real-world task. The next chapter describes the Usability Study conducted to gauge the usability and efficacy of the HFIRM prototype, and to gather information regarding opportunities for future improvement.

Usability Study

The Usability Study chapter discusses the objectives of the usability study and the methods used to develop and conduct the study. This chapter also presents the results of the study along with a preliminary analysis.

Objectives

The objective of the usability study was to generate information regarding the usability of the HFIRM prototype, the computer-based human performance analysis tool described in the previous chapter. Specifically, the study targeted the three primary measures of usability identified by Jordan et al. (1996): effectiveness, efficiency, and user satisfaction. Additional information was gathered through researcher observation of users operating the prototype. The purpose of this study was to identify trends in users' perceptions of specific elements of the tool, and to interpret the feedback in order to gauge face validity and guide future development activities.

The formal usability study represents one of several ways that feedback regarding this research was gathered. Expert verification was informally solicited and utilized throughout the development of the HFIRM~~HPAT~~ prototype, and had a significant impact on the design of the methodology. This chapter, however, focuses on the more formal usability study conducted to gather information from end-users.

Methods

This usability study was designed and conducted in accordance with Oregon State University Institutional Review Board (IRB) requirements, and with the formal approval of the IRB. This study was exempt from full board review, and was officially approved on April 18, 2008. The IRB Protocol for the Initial Application and the Informed Consent Form are available in Appendix B and Appendix C, respectively.

In order to support the three objectives of assessing effectiveness, efficiency, and user satisfaction in order to inform future development, the study incorporated standard design elements of both formative and summative evaluation as described by Scriven (1991). Summative evaluations are intended to gauge efficacy (i.e. the extent to which a product fulfills its intended purpose). They are typically conducted on a final product in order to generate statistically significant results. In contrast, formative evaluations gather information regarding the product during the development phase. Formative evaluations provide a basis for improvement, and inform design modifications and additional investments. They are typically conducted on a prototype and on a smaller scale. Formative evaluations range in their formality, and can include both expert and learner verification (Scriven, 1991).

Participants in the usability study performed at least two task analyses. During the first analysis participants~~they~~ analyzed specific system tasks in order to identify potential errors and design requirements that would prevent or mitigate the errors. The systems analyzed were within the aviation and medical industries. Participants performed the first task analysis using a basic Failure Modes and Effects Analysis template (Stamatis, 1995), and without any formal analysis tool to aid in the identification of failure modes. Participants conducted t~~During t~~he second task analysis ~~the participants analyzed tasks o~~in the same system for the same purpose as the first task analysis. ~~However, the series of first task analyses were performed using only a basic Failure Modes and Effects Analysis template, and without any formal analysis tool to aid in the identification of failure modes.~~ However, participants conducted the ~~T~~second~~ set of~~ task analysi~~e~~s with the aid of the HFIRM prototype. Upon completion of the second task analysis participants completed a written questionnaire regarding their experience using the HFIRM prototype in comparison to conducting the task analysis unaided.

Participant population

As described in the Development chapter the resource requirements for implementing HFIRM are a process model of the target system broken down to the task level, a system expert, and a human factors experts. The resource requirements significantly constrained the participant population that could be recruited for the usability study. The Spring 2008 IE 546 class was identified as an acceptable participant population because the central project for the class required modeling a real-world process and conducting a human factors analysis in order to improve system performance. Most students were familiar with human factors principles from previous course work, and an additional human factors overview was provided during the IE 546 class. Successfully completing the assignment required students to develop both a detailed understanding of the system as well as a task model. As a result, the three critical resource requirements for conducting the analysis were at least partially fulfilled. While the competency level of some students fell short of expertise in both system and human factors knowledge, their fluency in the subject areas was considered sufficient given the constraints and objectives of the usability study.

Seven of the eight students in the Spring 2008 IE 546 class chose to participate in the study (an 87.5% participation rate). While a sample size of seven is usually too small to establish statistically significant results, it is consistent with the low sample sizes frequently used in usability testing. In usability studies conducted by Nielson (1993), 80% of usability issues were uncovered by only five participants. Virzi (1992) reports similar results, and argues that given the limited resources available for usability testing small scale usability studies are a practical and viable way to identify the majority of usability issues. Virzi (1992) applies the law of diminishing returns to usability testing, asserting that in real-world usability testing, the cost-savings associated with relaxing statistical rigor outweigh the marginal benefits of increasing the sample size above five.

While small scale usability testing may be a practical necessity, there is evidence in the usability field that limited replications reduce validity. Faulkner (2003) presents results from a sixty participant usability study indicating that five subjects is an inadequate sample size to estimate experimental error. In Faulkner's study the responses from the sixty participants were divided into random subsets of five. The subsets of five users demonstrated significant variability in the number of usability issues that they identified. Relative to the usability issues identified by the entire participant population, some of the subsets of five users found 99% of the total usability issues, while others found only 55%.

One of the primary concerns regarding small sample sizes for usability studies is that there will not be representation of an appropriate range of expertise levels among the participants. Experts and novices tend to identify different types of usability problems. Novices frequently identify a large number of usability issues, while experts tend to identify a small number of severe issues (Faulkner, 2003). This concern is minimized in this study because the participants range in their expertise levels.

The purpose of the usability study is another important factor to consider when identifying an adequate sample size. While the glaring issues are usually identified by just a few users, more testers are required to find subtle and low-severity problems (Faulkner, 2002.) Based on the constraints and objectives of this study, seven testers were considered sufficient to identify high-priority usability issues, establish preliminary face validity, and provide feedback regarding the prototype that would be useful in the next development cycle.

Instruments

Creswell (2003) describes three common designs for research instruments: qualitative, quantitative, and mixed method. The mixed method approach employs both quantitative and qualitative questions. One strength of the mixed method approach is that ambiguous or unexpected results for quantitative questions can often be clarified by analyzing the qualitative responses (Creswell, 2003). Patton (1987) provides additional support for the mixed method approach because qualitative questions can be designed to complement quantitative questions by capturing the user perspective without limiting the expression of feedback through specific close-ended questioning structure (Patton, 1987). Therefore, this research study employs a mixed method approach that uses both quantitative and qualitative questions.

According to Patton (1987) one of the primary benefits of questionnaires is that they allows researchers to gather both qualitative and quantitative information without compromising participant anonymity. Additionally, questionnaires commonly require a relatively small time investment from participants and are inexpensive to produce. Based on these strengths the questionnaire was identified as the most appropriate research instrument for this usability study.

As explained above, the research study employed a mixed method approach that included open-ended qualitative questions and targeted quantitative questions, using a questionnaire as the research instrument. The purpose of the questionnaire was to gather information from end-users regarding the perceived usability and efficacy of the HFIRM prototype. A 5-point Likert-style response scale was used for the quantitative questions. Likert (1932) adapted social psychology theories to meet the practical requirements of applied study research through the development of a response scale which is now widely known as the Likert scale. The Likert scale is a one-dimensional scaling method that measures degrees of agreement with various survey statements (Likert, 1932). In the 5-point version of the Likert scale used for this research, a response of 1 indicates strong agreement and 5 indicates strong disagreement with the statement. In the questionnaire developed for this study, quantitative questions were framed as positive statements about specific characteristics of the analysis prototype (i.e. measures of usability or efficacy). The Likert-style response scale used in this study is presented in Table 16.

Table 16: Response key for quantitative questions

Level of Agreement	**Numerical Response**
Strongly Agree	1
Somewhat Agree	2
Neutral	3
Somewhat Disagree	4
Strongly Disagree	5

Twenty quantitative questions were created to gauge participants' perceptions regarding specific elements of the usability of the HFIRM prototype. The structure and syntax of the questions used in this study were informed by principles of sound questionnaire design such as those proposed by Fowler (2001). Fowler emphasizes the need to use simple words whose meaning is widely understood, to employ consistent phrasing, and to create series of questions that flow smoothly from one to the next (Fowler, 2001).

The content of the questions reflects the objectives of the study and the goals of the original research. The questions were designed to address the three primary measures of usability identified by Jordan et al (1996): effectiveness (the ability of users to complete analysis steps using the prototype, and the quality of the output of the analysis), efficiency (the level of resources required to perform an analysis using the prototype), and satisfaction (users' subjective perceptions of the prototype). The development of each question, and its importance within the context of the study objectives and research objectives, is explained below.

Eleven quantitative questions addressed the usability of the prototype, specifically the extent to which specific elements of the HFIRM prototype affected the ability of users to complete the analysis steps and the subjective user satisfaction with the prototype. Because the purpose of the questionnaire was to provide guidance regarding future design changes, usability questions targeted specific elements of the prototype in order to identify potential development opportunities. Important measures included the extent to which the format and organization of the prototype content promoted the effective transfer of information (i.e. clarity and comprehensibility), the ease of use of the interface, and the functionality of the software.

Each of the primary functions that users perform in order to operate the HFIRM prototype was addressed in the usability questions. These functions include reading and understanding the instructions, descriptions, buttons, and labels on each MS Access form. Additionally, successful use of the prototype requires users to navigate through the MS Access forms, to develop an understanding of the purpose of each step in the methodological procedure, to use the information provided on each form to make correct selections, to select items from list boxes, and to take the appropriate action to progress to the next form at the right time. One important subjective measure of usability for the prototype is how reasonable analysts feel the amount of information returned/ presented in each form is. An additional subjective measure of usability is how confident users are that their selections are correct. Feedback regarding each of these primary functions of the prototype was solicited through the eleven questions below:

Usability questions:

1. The instructions on each page were clear and easy to understand.
2. I was able to navigate through the pages without difficulty.
3. I understood the purpose of each step in the process.
4. The definitions and descriptions on each page helped me make the correct selections.
5. It was clear to me how to select items from the list boxes.
6. It was clear to me where I needed to click in order to progress to the next page in the process.
7. Headings and buttons were clearly labeled.
8. The pages were easy to read.
9. I was able to confidently determine which Human Information Processing stages were employed during the target task.
10. I was able to confidently determine which Necessary Conditions were present during the target task.
11. The quantity of information that I had to choose from on each page was reasonable.

The eleven usability questions gathered information regarding the extent to which users were able to complete critical functions using the prototype, and their satisfaction with these functions. The subsequent nine questions in the questionnaire were focused on the results of the analysis. They were designed to measure the quality of the output of the analysis, which was the second component of effectiveness identified by Jordan et al (1996). These questions gauged the efficacy of the HFIRM prototype (i.e. the extent to which it fulfills its intended purpose) based on user-satisfaction with the results. The objective of the HFIRM prototype is to provide analysts with information relevant to the identification and remediation of human errors. Therefore, the efficacy questions addressed the extent to which users perceived that the analysis helped them identify human errors and appropriate remediation strategies.

Nine quantitative questions were designed to address the perceived efficacy of the HFIRM prototype, specifically the quality, quantity, and novelty of the information returned by the analysis and its contribution to the identification of potential errors, adverse events, and appropriate remediation techniques. Information regarding the quality of the results and user satisfaction with those results was gathered through the following efficacy questions:

12. The analysis tool identified potential human fallibilities that I would not have identified without the tool.
13. The potential Human Fallibilities returned by the analysis helped me identify potential human errors.
14. The Human Factors Guidelines returned by the analysis helped me determine the probability and severity of the threat posed to the system.
15. The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes.
16. Conducting the analysis using the analysis tool yielded more thorough results than conducting the analysis unaided.
17. Conducting the analysis using the analysis tool yielded more valuable results than conducting the analysis unaided.
18. Using the analysis tool increased the effectiveness of my analysis.
19. I preferred conducting the analysis with the tool, as opposed to without it.
20. I will choose to use the tool the next time I conduct a human factors analysis, if it is available.

The quantitative questions described above facilitated the comparison and precise analysis of the ender-user perception of specific elements of the HFIRM prototype. Four open-ended qualitative questions complemented the quantitative questions by providing participants with an opportunity to provide feedback regarding the strengths, weaknesses, opportunities for development, and general suggestions for the HFIRM prototype. Additionally, four questions were posed to participants in order to gather information regarding the amount time they spent conducting the analysis and number of potential errors they identified when using the HFIRM prototype versus conducting the analysis unaided. These questions were designed to measure the efficiency of the analysis. The questionnaire developed for this usability study is included in Appendix D, and the responses received are presented in the Results and Analysis section.

Study Procedure

Participants were recruited from the Spring 2008 IE 546 class. As part of an IE 546 course assignment, students were required to conduct human factors analyses both unaided and using the human factors analysis tool of their choice. During the IE 546 course students were taught how to conduct human factors analyses and were introduced to several existing analysis tools, including the Human Performance Analysis Tool (HFIRM). Students were introduced to HFIRM through a thirty minute informative session, conducted by the author, which provided an overview of the HFIRM purpose and methodology, and walked the students through an example analysis.

Students used a Failure Modes and Effects Analysis template to conduct their first "unaided" analysis of several system tasks. Participants used the HFIRM prototype to conduct their subsequent aided analyses of between one and three system tasks. The tasks analyzed were from complex real-world systems. For example, one of the tasks analyzed was the selection of appropriate machine setting when preparing to defibrillate a patient in Advanced Cardiac Life Support.

Six of the seven participants conducted the analysis in the presence of the researcher, allowing informal observation. After completing the analysis using the

HFIRM prototype, participants completed a written questionnaire about their experience with the analysis tool. Information regarding the participant responses is presented in the Results and Analysis section.

Results and Analysis

The Results and Analysis section presents the information gathered from participants both through their questionnaire responses and through researcher observation. This section examines the results of the qualitative and quantitative questions and identifies significant trends.

Questionnaire Results

The primary results indicate that users positively perceived both the usability and the efficacy of the HFIRM prototype. All participants reported that they identified more potential errors in less time when using the HFIRM prototype relative to performing the task analysis unaided. Participants reported spending between 15 and 90 minutes conducting the analysis using the HFIRM prototype. In contrast, participants reported spending between 30 and 120 minutes conducting the analysis unaided. Full questionnaire responses for each participant are provided in Appendix E. Summary statistics for the quantitative questions are presented in Appendix F.

As previously discussed, quantitative responses were scored on a 5-point Likert scale, with 1 indicating strong agreement and 5 indicating strong disagreement with various positive statements regarding the tool. Responses to the quantitative questions were generally positive. The mean score for questions addressing the usability of the tool was 1.78, where a score of one indicates strong agreement with various positive usability measures. Amongst usability questions, the questions with the poorest mean scores (both with means of 2.29) were, “I was able to confidently determine which Human Information Processing stages were employed during the target task,” and “The quantity of information that I had to choose from on each page was reasonable.” Box and whiskers plots for the quantitative usability questions are presented in Figure 23.

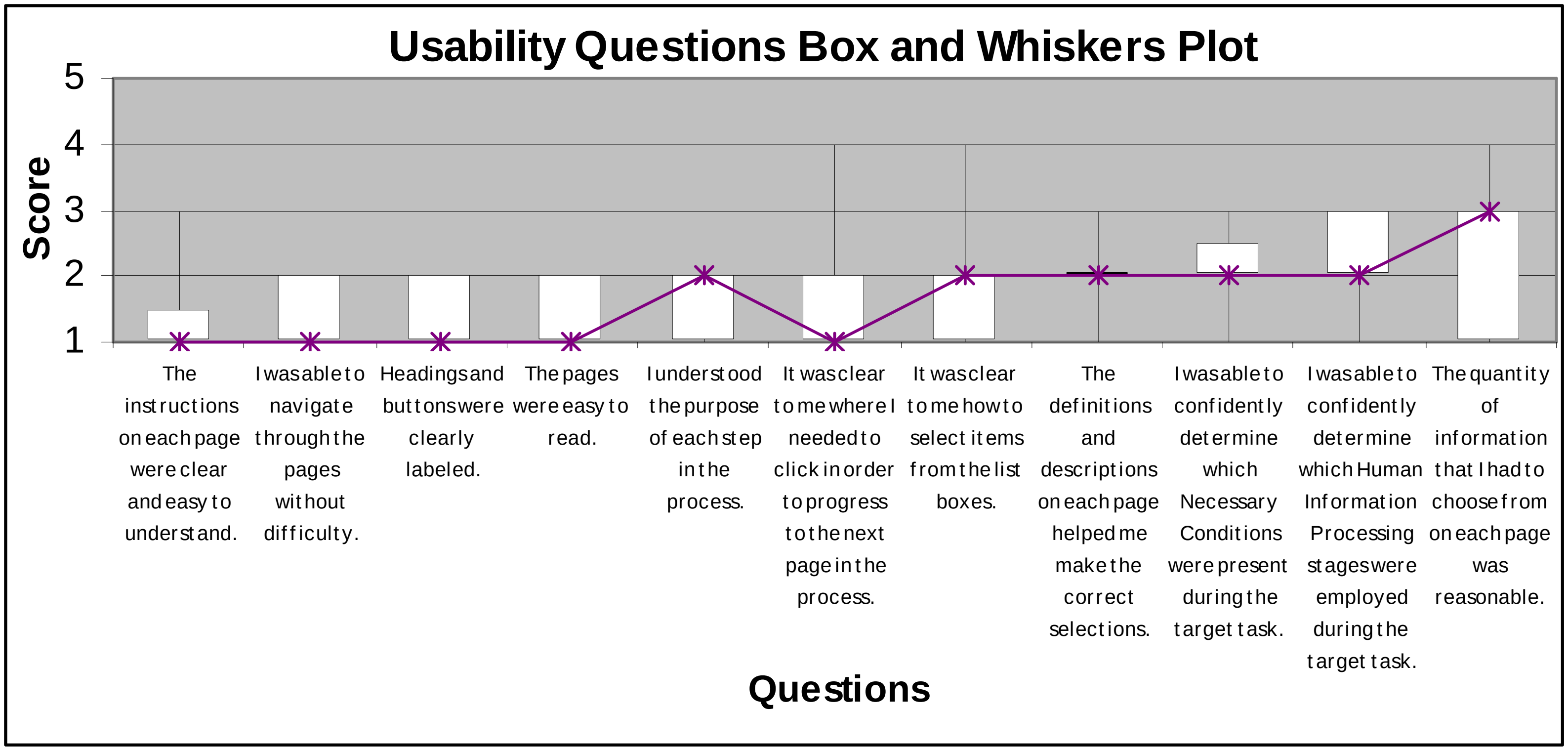


Figure 23: Box and whiskers plot of the usability question results

Nine quantitative questions focused on the efficacy of the HFIRM prototype. The mean score for questions addressing the efficacy of the methodology was 1.39, substantially better than the mean usability question score of 1.78. The highest scoring efficacy question was “The analysis tool identified potential human fallibilities that I would not have identified without the tool,” and received unanimous strong agreement (mean=1) from all participants. The lowest scoring efficacy question was “The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes,” which received a still-positive score of 1.71. Box and whiskers plots for the quantitative usability questions are presented in Figure 24.

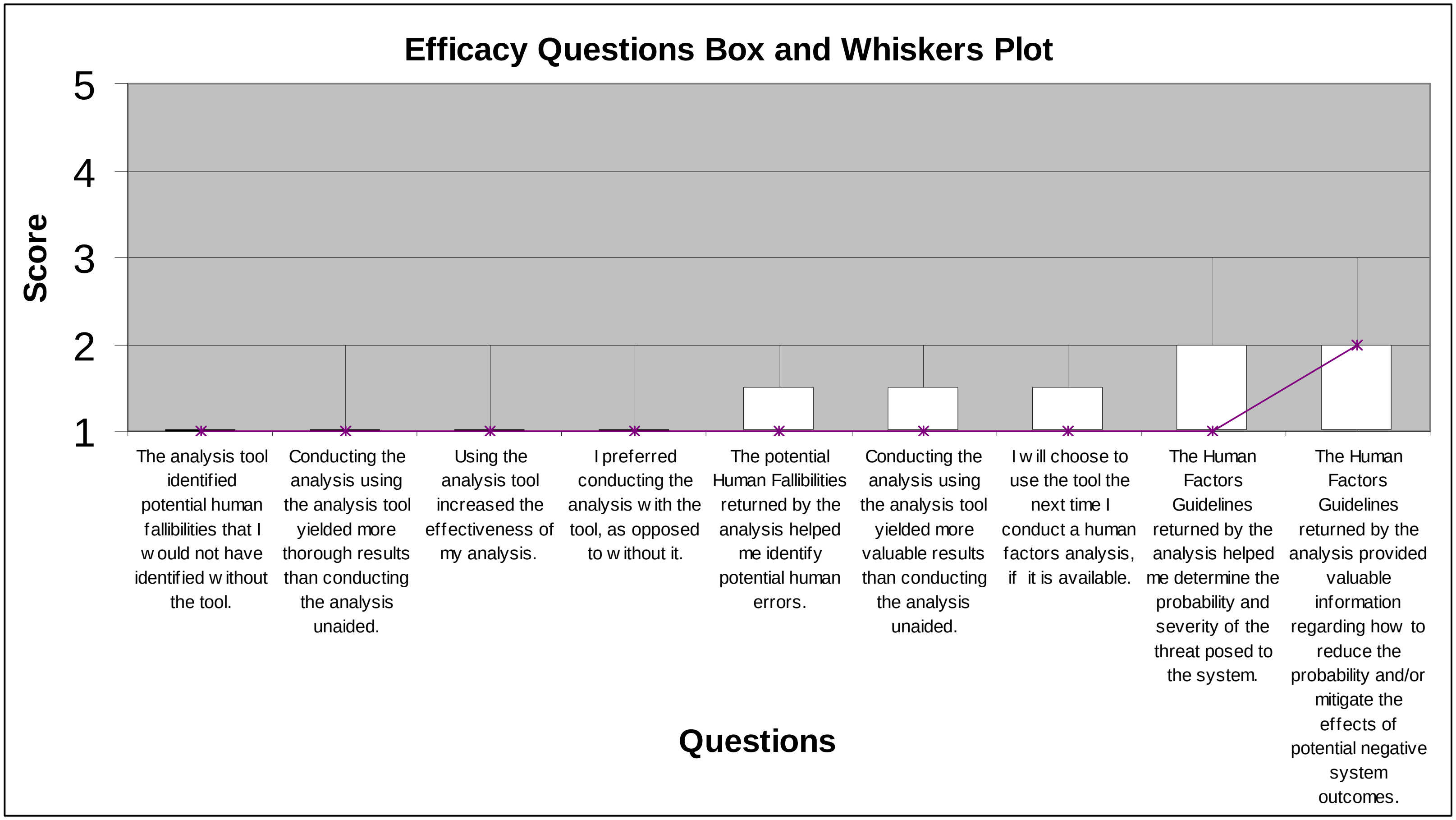


Figure 24: Box and whiskers plot of the efficacy question results

Qualitative questions supplemented the structured quantitative questions by asking participants to list the top three strengths, weaknesses, and recommendations for the HFIRM prototype. The responses were grouped into four general categories based on the element of the tool that they addressed: content, method, format/interface, and efficacy/functionality. Qualitative responses organized by participant are listed in Appendix E: Appendix Table 2. Qualitative responses organized by subject category are displayed in Appendix G.

Multiple participants identified comprehensiveness of the database content, the simplicity of the methodology, and the quality of the results as the primary strengths of the analysis tool. Commonly cited weaknesses included difficult to understand definitions, information proliferation, redundancies in the information presented, and lack of a “back” button. The top recommendations for improvement were to add a “back” button, eliminate redundancies in information presented, and decrease the quantity of information returned at each step. Excerpts from the qualitative question responses are grouped by subject and presented in Table 17.

Table 17: Excerpts from the qualitative question responses grouped by category

	Content	**Method**	**Format/ Interface**	**Efficacy / Functionality**
Strengths	• Very clear • H-F database	• Analysis is complete in a few steps	• Simple easy interface • Relatively easy to use	• Provides really good human fallibilities • Reduces my workload
Weaknesses	• Some definitions were difficult to understand or cut off	• Information Overload • Too much reading	• Fallibility repetitions • Couldn't adjust selection screen sizes • Microsoft Access is a pain	• Time consuming • No back button
Recommendations	• Make human fallibilities more clear	• If selectivity could be increased in some fashion, that would be useful	• Eliminate Redundancies • Make it a stand alone application, like a web interface	• Please include back button

Researcher Observations

The following observations were made by the researcher during observation of the students using the HFIRM prototype.

- Most participants did not read either the introductory instructions on Form 0 or the instructions on the top of each subsequent form.
- Participants had difficulty differentiating characteristics of the target task from the characteristics of the process.
- Lack of human factors knowledge impeded the participants' understanding and ability to respond to prompts for information regarding the target task.
- Participants demonstrated automation over-dependency, and were reluctant to invest in the careful consideration of the information requested and presented throughout the analysis.
- Students were confused by the "Select All" functionality on Step 2 and Step 4, and as a result they viewed these steps as redundant.
- Lack of human factors expertise hampered students' abilities to use human factors information returned in the Guidelines section to identify potential errors, probability, and severity.
- The Guidelines that were most useful to students were those that were presented as imperative statements (i.e. commands), because they could be inserted directly into the system requirements without further reflection.

The Discussion chapter addresses the significance of the information gathered during the usability study in the context of the HFIRM prototype objectives and the implications for future design cycles.

Discussion

This chapter critically analyzes the results of the usability study in light of the objectives of the research and generates potential remediation strategies for the issues identified. The methodology goals are revisited and the extent to which they have been achieved is discussed. Finally, the HFIRM prototype is considered in the context of the Critical Dimensions of Human Performance Models introduced in the Literature Review chapter.

Usability Study Discussion

This section evaluates the results of the usability study based on the objectives of the thesis. Information gathered from the quantitative and qualitative usability study questions and researcher observations is synthesized, and its significance within the context of this research is discussed. The potential underlying causes of survey response trends are explored, and targeted improvement strategies are proposed.

The HFIRM prototype is intended to be used by human factors experts and system experts working in cooperation. As discussed in detail in the Usability Study chapter, due to the constraints of the usability study some participants fell short of the desired proficiency level in both their system and human factors expertise. While it seems likely that lack of expertise influenced subjects' responses to some degree, preliminary examination of the questionnaire results revealed no clear trends between responses and participant expertise. Therefore, this discussion will focus on explanatory factors and potential remediation strategies that look beyond the expertise of the participants to the design and function of the HFIRM prototype.

The quantitative questions in this usability study were scored on a scale of 1-5, where 1 represented strong agreement and 5 represented strong disagreement with various positive statements about the HFIRM prototype. The worst score received by any question was a 4 ("somewhat disagree"), and no question received a 4 from more than one of the seven participants. Every question received a 1 ("strongly agree") from at least one participant. Box and whiskers plots for the quantitative usability and efficacy questions are presented in Figure 23 and Figure 24 respectively.

The quantitative question that received the best mean score overall was, "The analysis tool identified potential human fallibilities that I would not have identified without the tool." This question received a mean score of 1, indicating unanimous "strong" agreement. The quantitative question that received the worst mean score overall was, "I was able to confidently determine which Human Information Processing stages were employed during the target task." This question received a mean score of 2.29 (2 indicates "somewhat agree," and 3 indicates "neutral"), which is still above the midpoint of the scoring scale. The fact that no question received a mean score of worse than 2.29 reflects positively on participants' experiences with the HFIRM prototype.

The mean score for quantitative usability questions was 1.78. Table 18 presents the quantitative usability questions in rank order from best to worst mean score. Four of the questions received mean scores of 2 or worse. The four worst scoring questions (Ranks 8-11) all concern the quantity and clarity of the information presented to users during the analysis. Several factors may have contributed to this trend. The 8^{th}, 9^{th}, and 10^{th} ranked questions all address the extent to which analysts felt that they were able to use information presented during the analysis to confidently make correct selections. The 9^{th} ranking question, with a mean score of 2.14, was "I was able to confidently determine which Necessary Conditions were present during the target task." Participants indicated slightly less strong agreement (mean score of 2.29) with the 10^{th} ranking question, "I was able to confidently determine which Human Information Processing stages were employed during the target task."

Table 18: Quantitative usability questions ranked by mean score from best to worst

Rank	Question	Mean	Range
1	The instructions on each page were clear and easy to understand.	1.43	2
2	I was able to navigate through the pages without difficulty.	1.43	1
3	Headings and buttons were clearly labeled.	1.43	1
4	The pages were easy to read.	1.43	1
5	I understood the purpose of each step in the process.	1.57	1
6	It was clear to me where I needed to click in order to progress to the next page in the process.	1.71	3
7	It was clear to me how to select items from the list boxes.	1.86	3
8	The definitions and descriptions on each page helped me make the correct selections.	2.00	2
9	I was able to confidently determine which Necessary Conditions were present during the target task.	2.14	2
10	I was able to confidently determine which Human Information Processing stages were employed during the target task.	2.29	2
11	The quantity of information that I had to choose from on each page was reasonable.	2.29	3

Lack of strong confidence amongst participants in their ability to accurately identify Human Information Processing stages and Necessary Conditions is problematic because the methodology relies on this information to identify potential human fallibilities. Like many other analysis methods, HFIRM is a “garbage in-garbage out” system in that the accuracy of its output is dependent on accurate inputs. Therefore, it is critically important to present information to analysts in a form that allows them to confidently and correctly identify relevant task factors.

Several strategies can be readily implemented to improve analysts’ confidence in their selections. The first requires using language that requires less technical expertise to understand. The information in the human factors database was written for an audience of human factors experts. However, while technically advanced language can be both efficient and expressive, it frequently does not promote quick and easy comprehension of the material. Additionally, it requires analysts to perform the extra step of translating human factors vocabulary into the common vernacular before applying it to domain-specific tasks. Adjusting the language in the database to emphasize clarity and simplicity has the potential to increase the speed and ease with which analysts can apply the information to specific systems and tasks.

Human Information Processing Stages are highly theoretical, and providing examples of commonly associated task types and verbs may help promote analyst understanding of the relationship between these concepts and the target task. For example, Decision Making is a Human Information Processing Stage frequently associated with evaluating, judging, and inferring. Relating the abstract stages of the human information processing model to common activities may help analysts accurately and confidently identify the specific Human Information Processing Stages employed during the target task. Additionally, the stage model of human information processing may be clarified by displaying a spatial diagram of the model that illustrates the relationships between stages.

The strategy of using examples to illustrate abstract concepts can also be employed to help analysts determine which Necessary Conditions are present in their systems. While Necessary Conditions often refer to specific physical activities or system characteristics, they can also refer to abstract cognitive processes such as the allocation of attention. To the extent possible, Necessary Conditions should be clarified through clear and commonly encountered examples.

The quantitative usability question that received the worst mean score was, "The quantity of information that I had to choose from on each page was reasonable." Proliferation of information was a serious concern throughout the development of the HFIRM prototype. The efficiency of any methodology in terms of the investment required to conduct the analysis is a key determinant of its practical viability. Several participants also alluded to information proliferation as a weakness of the model in their qualitative responses.

During the development of the analysis method and the supporting database, efforts were made to organize information in a narrow and deep structure, so that by responding to relatively few prompts for information users could access comprehensive and accurate information regarding potential fallibilities for the target task. The database currently contains over a thousand instances of concepts (e.g. Human Information Processing Stages, Human Fallibilities, etc.), with the potential to add significantly more information. One of the primary challenges during the development of the analysis methodology and the human performance ontology was to create a filtering scheme that quickly and accurately identifies the small subset of human performance information that is relevant to the target task. Further refinement of both the methodology and the ontological structure has the potential to reduce the amount of information analysts need to consider in order to secure meaningful results.

When considering potential changes to the methodology in order to decrease the amount of information analysts need to consider, there are two promising opportunities that require minimal effort to implement. The first involves narrowing the definition of a “task.” Currently, the resource requirements specify that a system model that represents processes to the task level is needed to conduct the analysis. However, this definition can be interpreted very broadly. When analysts use HFIRM to analyze tasks that are very complex, more human information processes stages tend to be employed during the task. As a result, more Necessary Conditions are returned to analysts for consideration. In most cases, the amount of information returned to the user during each step of the analysis increases with the complexity of the task. The most straightforward remedy for this is to strictly define the meaning of “task” for the purposes of the analysis. For example, a task may be defined as a goal-oriented activity during which no more than four human information processing stages are employed.

The reason that constraints were not placed on the definition of task during this research is because doing so threatens the efficiency of the analysis. Breaking tasks down beyond a certain point obscures their relationship to the system goals and to other tasks and high level processes. Additionally, each time a single task is reduced to several sub-tasks, the number of tasks to be analyzed increases exponentially. When defining what constitutes a task, a balance needs to be maintained between information proliferation and task proliferation.

As noted in the research observations, participants struggled to differentiate the activities involved in the task from the processes involved in the system. As a result, they frequently included human information processes stages and necessary conditions that were present in the system, but not central to the target task. This is a potential issue for any reductionist method, and has the potential to be especially problematic when the system involves continuous processes that encompass multiple tasks. One strategy that may mitigate the confusion in the short-term is to emphasize and reiterate that the focus of the analysis is the target task, and to encourage analysts to clearly define the boundaries of the task and its relationship within the larger system.

In the long run, it may be necessary to explore more sophisticated solutions to the problem of task/system ambiguity. Currently the foundational ontology and the resulting Human Factors Database both utilize precise predicate logic, i.e. Human Information Processing Stages are either employed during the task or they are not. However, this type of true/false logic is not fully consistent with the nature of the concepts in the Human Fallibility Database. For example, Attention Allocation is a Human Information Processing Stage that is central to search tasks, but it is at least tangentially involved in almost all human activities.

One way to address the inherently imprecise nature of the concepts in the Human Fallibility Ontology is to incorporate fuzzy logic into the relationship structure. Fuzzy ontologies merge fuzzy logic with ontological representation of knowledge (Parry, 2004). "Fuzzification" of a standard ontology involves assigning membership values to currently existing relationships. Instead of absolute relationships, the fuzzy ontology incorporates levels of relatedness between concepts. The structure of a fuzzy ontology is more complex than that of the standard ontology; however it also has the potential to increase the ability of the ontological framework to describe inherently imprecise relationships.

The mean score for quantitative efficacy questions was 1.29, which indicates strong to somewhat strong agreement with positive statements regarding the efficacy of the tool. The three best scores (Ranked 1-3) compare the two analyses conducted by participants. The first “unaided” analysis was conducted using only a basic Failure Modes and Effects Analysis (FMEA) template. The second analysis was conducted using the HFIRM prototype. Responses indicate that participants preferred using HFIRM, and felt that using the tool increased the effectiveness of their analysis and allowed them to identify potential human fallibilities that they would not have otherwise identified. Table 19 presents the quantitative efficacy questions in rank order from best to worst mean score.

Table 19: Quantitative efficacy questions ranked by mean score from best to worst

Rank	Question	Mean	Range
1	The analysis tool identified potential human fallibilities that I would not have identified without the tool.	1.00	0
2	Conducting the analysis using the analysis tool yielded more thorough results than conducting the analysis unaided.	1.14	1
3	Using the analysis tool increased the effectiveness of my analysis.	1.14	1
4	I preferred conducting the analysis with the tool, as opposed to without it.	1.14	1
5	The potential Human Fallibilities returned by the analysis helped me identify potential human errors.	1.29	1
6	Conducting the analysis using the analysis tool yielded more valuable results than conducting the analysis unaided.	1.29	1
7	I will choose to use the tool the next time I conduct a human factors analysis, if it is available.	1.29	1
8	The Human Factors Guidelines returned by the analysis helped me determine the probability and severity of the threat posed to the system.	1.57	2
9	The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes.	1.71	2

Two of the questions received mean scores of 1.5 or worse. Both of these questions (Ranked 8 and 9) address the extent to which analysts were able to effectively utilize the human factors information provided in the guidelines to estimate the probability and severity of domain-specific potential errors, and to develop appropriate remediation techniques. The methodology is designed so that the analysis guides the user through a series of targeted questions and prompts. Once the potential human fallibilities and associated guidelines are displayed the analysis becomes less structured.

The relatively loose structure of the Error Identification and Remediation phase is intended to allow users to consider and utilize the human factors information as appropriate for their purposes and system. Based on their objectives, analysts may choose to consider potential fallibilities in depth, or focus on only the fallibilities that they perceive to be most threatening to their system. The Error Identification and Remediation phase allows analysts the flexibility to determine how they will translate targeted human factors information into domain-specific errors and remediation strategies, and provides notation fields so that they can document their ideas.

While flexibility is important during the Error Identification and Remediation phase, both questionnaire data and researcher observations suggest that providing a more structured analysis framework may increase the ability of users to apply the human factors information to their system. While flexibility is an important methodology goal, flexibility must be balanced with the necessity of providing adequate guidance to promote the systematic consideration of human factors information in the context of the target task.

Two complementary approaches are available to increase the guidance provided to analysts as they translate targeted human factors information into domain-specific errors and remediation strategies. The first involves increasing the sophistication of the ontology “Guideline” concept by defining additional attributes and relationships for the guidelines. Currently several types of information are grouped together under guidelines, including system factors that influence the probability of error and human factors design principles. Distinguishing between these information types may assist analysts in determining how the information applies to their system. The second way to augment the guidelines to facilitate the identification and remediation of potential errors is to extend the methodology to define specific procedures for utilizing the guidelines. These steps need to be defined specifically enough to be implemented, yet still retain the flexibility to be applicable across domains.

One promising opportunity that involves both the reorganization of the guidelines and the extension of the methodology is to integrate principles of Failure Modes and Effects Analysis (FMEA) into the Error Identification and Remediation phase of the methodology. The HFIRM prototype currently returns information regarding the potential human fallibilities which can be manifested during the target task. These potential fallibilities provide the critical information needed to identify FMEA failure modes. The human factors information that is currently presented in the Guidelines may be differentiated based on the FMEA framework, and presented as relevant to the detectability, severity, probability or effects of potential errors.

Increasing the structure of the human factors guidelines has the potential to contribute directly to the ultimate purpose of the methodology: the identification and remediation of potential errors. The information presented in the guidelines is the primary mechanism through which analysts are expected to identify potential errors. Future design efforts should emphasize the organization and presentation of this information in order to facilitate its systematic application to the target system.

The qualitative usability study questions and researcher observations also identified two key issues that were not captured by the quantitative questions. The first major usability issue that was identified by both the qualitative responses and researcher observation was the need for a “Back” button. This was a known issue that had previously been documented for future development cycles, but which was not implemented for the HFIRM prototype because it is well outside the scope of the project.

The second, and substantially more complex, usability issue is that of redundancy. Based on expert feedback early in the design of the MS Access form-query structure, two forms were added that were intended to increase the flexibility of the analysis. Step 2 displays all of the human fallibility categories that may be manifested during the target task. Figure 25 displays a screen shot of Step 2 for reader reference. Step 4 displays all of the specific human fallibilities that may be manifested during the target task. Each form instructs users to either “Select All” for a complete analysis, or to choose only the fallibilities that they would like to continue to analyze.

These forms were intended to provide advanced users with a convenient way to selectively analyze the potential impact of a small number of fallibilities on the target task. However, as noted in the researcher observations, analysts frequently did not read the instructions at the top of each form. Most did not check the “Select All” box, but instead attempted to choose fallibilities based only on their names and definitions. As a result, users experienced significant confusion, frustration, and time delays. It is possible that confusion could be reduced by making the “Select All” box more salient, and by emphasizing the conditions under which users should attempt to select specific human fallibilities.

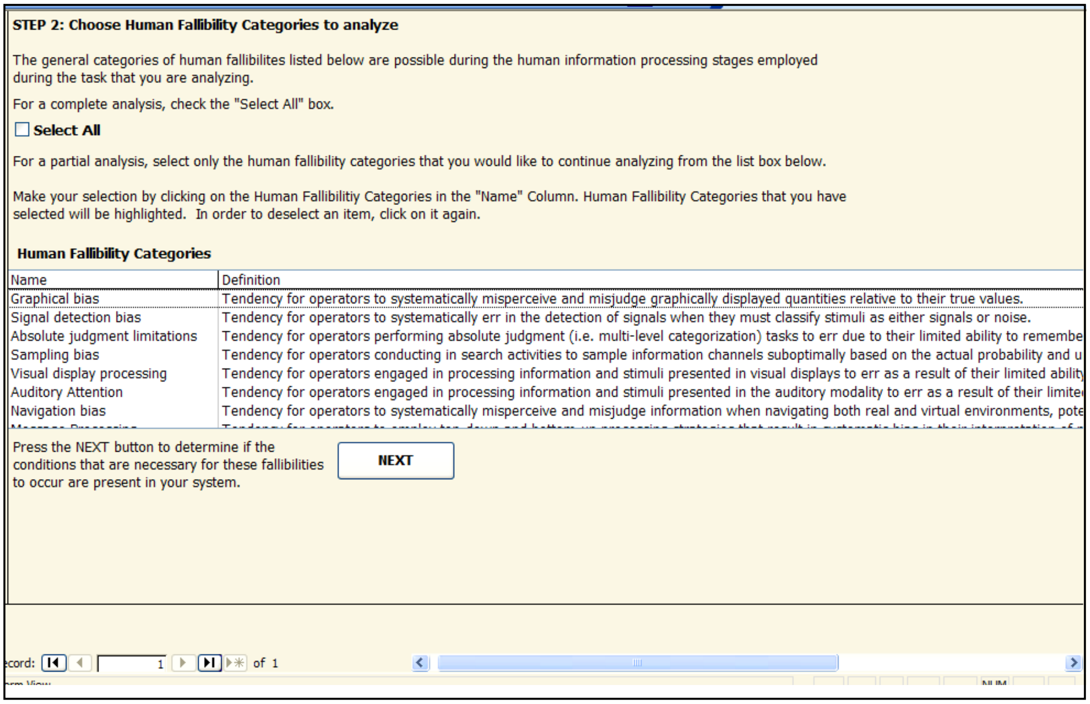


Figure 25: Participants failed to appropriately use the “Select All” box in both Step 2 and Step 4.

Participants also identified redundancies on Step 5 that decreased the efficiency of the analysis. Based on expert feedback, enhancements were made to both Step 3 and Step 5 early in the design cycle. Initially, each form displayed only a list of Necessary Conditions. In order to provide users with some context around the Necessary Conditions, the Human Fallibility Category (Step 3) or Human Fallibility (Step 5) associated with each Necessary Condition was also displayed. Due to programming constraints, the enhancement to Step 5 was not executed as envisioned. Database relationships are structured so that each Necessary Condition may apply to multiple fallibilities. As a result, on Step 5 the same Necessary Condition is frequently displayed multiple times, each time next to a different Human Fallibility. Users perceived this repetition as redundancy. See Figure 26 for an explanatory screen shot of Step 5. Eliminating this repetition by restructuring the query logic is an opportunity for future development.

STEP 5: Identify the Necessary Conditions that are present

The table below displays Human Fallibilities (in the "Name" column) and the Necessary Conditions that must be present during a task in order for the Human Fallibilities to affect human performance (in the "Description" column).

Select the statements in the "Description" column that are true for the task that you are analyzing.

Make your selection by clicking on the Necessary Conditions in the "Description" Column. The Necessary Conditions that you have selected will be highlighted. In order to deselect an item, click on it again.

Select the statements below that are true for the system that you are analyzing.

Name	Description
Sluggish beta	Operators must discriminate between noise and signals in a spectrum of stimuli that may be difficult to differentiate.
Beta placement bias (individual)	Operators must discriminate between noise and signals in a spectrum of stimuli that may be difficult to differentiate.
Beta placement bias (expertise)	Operators must discriminate between noise and signals in a spectrum of stimuli that may be difficult to differentiate.
Sensitivity suboptimality	Operators must discriminate between noise and signals in a spectrum of stimuli that may be difficult to differentiate.
Vigilance Decrement (sensitivity decrement)	Operators must engage in signal detection activities for an extended period of time.
Vigilance Decrement (shift in beta)	Operators must engage in signal detection activities for an extended period of time.
Vigilance decrement (fatigue)	Operators must engage in signal detection activities for an extended period of time.

Figure 26: Repetition of Necessary Conditions in Step 5 was perceived as redundancy.

The usability study provided valuable information regarding user perception of the usability and efficacy of the tools. Positive responses to efficacy questions support the face validity of the HFIRM prototype. Trends identified during the usability study inform the fulfillment evaluation of the goals. Additionally, the usability study identified a substantial number of potential design enhancements and provided insight into how subsequent development resources should be allocated.

Evaluation of Goals

The Evaluation of Goals section discusses the extent to which the HFIRM prototype meets the research goals introduced in the Methodology chapter. This section also considers the relative strengths and weaknesses of HFIRM in light of the critical dimensions of human performance models introduced in the Literature Review chapter.

The objectives of this research were to design a human performance analysis tool that supports the identification and remediation of potential human errors. These objectives are ambitious, and set targets that no other existing human error analysis tool has fully achieved. The goals for the methodology and the database define the specific capabilities and characteristics that the analysis tool needs to have in order to achieve the overarching objectives of the research. In order to assess the extent to which these goals have been accomplished, this section compares the research goals to the current function, content, usability, and efficacy of the resulting HFIRM prototype.

The functional capabilities of the HFIRM prototype are apparent through examination of the MS Access form-query structure. Characteristics of the database content and relationships are identified through examination of the MS Access tables. Information regarding the usability and efficacy of the HFIRM prototype is drawn from the usability study.

Seven research goals were identified to support the objectives of this research. The extent to which each of these goals was met was classified into one of three levels: unsatisfactory, satisfactory, and complete. “Unsatisfactory” indicates that examination of the functional capabilities the HFIRM prototype and/ or the usability study results indicated that the goal was not achieved. “Satisfactory” indicates that the goal was achieved, however expert examination of the functional capabilities of HFIRM and/ or the usability study results identified ways in which the HFIRM could be augmented to more completely achieve the goal. “Complete” indicates that the goal was met and that no additional improvements that fall within the scope of this research were identified. Of these seven goals, five were judged to have been satisfactorily met, while two were completely met. Table 19 evaluates the extent to which each of the research goals was achieved, and provides comments that support the evaluations.

The primary factor preventing the complete fulfillment of several of the database goals (goals # 3, 4 and 6) was the structure of the human factors guidelines provided to users during the Error Identification and Remediation phase of the analysis. Although during the design and implementation of the tool these guidelines were considered to be sufficient, the usability study revealed that enhancing the organization of the content and the procedural rigor of this phase of the methodology may improve the identification of potential errors and appropriate interventions.

Table 19: Research goals evaluation

Eval	Goal number and description
+	[1] Generalizable: The methodology will be generalizable so it can be applied across domains.
	Comments: + Both the methodology and the database content are applicable across domains.
✓	[2] Efficient: The methodology will be efficient, i.e. The ratio of useful information derived from the analysis to the time spent conducting the analysis will be high; The performance analysis will be compatible with at least one existing process modeling technique, so that no novel process modeling technique will need to be developed or adapted in order to conduct the analysis.
	Comments: ✓ All participants in the usability study identified more potential errors in less time when using HFIRM than when using the FMEA template. ✓ Several usability study participants listed HFIRM's speed as a primary strength of the tool. + HFIRM is compatible with IDEF0, as well as other modeling techniques.
✓	[3] Systematic: The methodology will define a rigorous procedure for performing an information-driven human performance analysis of the target task; Human performance information that is relevant to the analysis will be contained within the model.
	Comments: + Rigorous procedure defined for Phases 1 and 2 - Additional structure needed for Phase 3 (Remediation). + Analysis draws on human factors knowledge during each phase + HFIRM provides information-rich prompts and human performance guidelines
✓	[4] Identification: The performance analysis shall support the identification of potential human errors and negative system outcomes.
	Comments: ✓ HFIRM returns human factors information regarding the potential human fallibilities and the errors that may result. ✓ Mean response to Usability study question "The potential Human Fallibilities returned by the analysis helped me identify potential human errors" was 1.29. - Additional structure in Error Identification and Remediation phase may improve error anticipation, user-centered design, and the development of effective countermeasures.
✓	[5] Prospective: The performance analysis will be applicable to complex systems in the design phase in order to improve error anticipation, user-

	centered design, and the development of effective countermeasures; The performance analysis will support the prospective analysis of system and human factors that increase the probability of human error.
	Comments: + Applicable during the design phase ✓ HFIRM returns human factors information regarding the preventative, mitigating, and contributing factors associated with potential human fallibilities and resulting errors. ✓ Mean response to Usability study question, “The Human Factors Guidelines returned by the analysis helped me determine the probability and severity of the threat posed to the system” was 1.57.
✓	[6] Remediation: The performance analysis will support the remediation and improvement of procedures, equipment design, and training methods.
	Comments: ✓ HFIRM returns preventative and mitigating conditions and human factors principles. ✓ Mean response to Usability study question, “The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes” was 1.71. - Additional structure in Error Identification and Remediation phase may improve error anticipation, user-centered design, and the development of effective countermeasures.
+	[7] Information-driven: The performance analysis will draw from a source of human factors information in order to support the identification and remediation of potential human errors and adverse events.
	Comments: + HFIRM draws human factors information from the Human Fallibility Database during each phase of the analysis.

KEY	
-	Goal not met
✓	Goal satisfactorily met
+	Goal completely met

The database goals support the achievement of the HFIRM prototype objectives by specifying elements of the design and function of the human performance database. Of the seven design goals, four were satisfactorily met while three were completely met. Of particular interest is goal #4, which states that the database shall be structured for flexible use. Two MS Access forms are dedicated to increasing the flexibility of the analysis by allowing users to view potential human fallibilities and either selectively choose which ones will be included in the analysis, or “Select all” for a complete analysis. Additionally, users are given the opportunity to enter notation for each guideline returned by the analysis, allowing them the flexibility to specify if and how they will use the information.

Numerous opportunities still exist to increase the flexibility with which users can access database content. These opportunities are further discussed in the Future Research and Development section of this chapter. Table 20 evaluates the extent to which each database goal was met and provides evidence that supports the evaluations.

Table 20: Design goals evaluation

Evaluation	Goal number and description/ Comments
+	1. The human performance database will capture relevant information from Engineering Psychology and Human Performance (Wickens and Hollands, 2000).
	Comments: + The human performance database contains 1045 instances of concepts extracted from Engineering Psychology and Human Performance (Wickens and Hollands, 2000).
+	2. The database will identify meaningful associations between human information processing stages, human fallibilities, system variables, and relevant human factors principles and guidelines.
	Comments: + The human performance database identifies 1805 relationships between objects.
+	3. Forms and queries will be designed to guide analysts through an information-driven fallibility analysis of a target task.
	Comments: + A series of seven forms draws information from the human performance database and guide users through the analysis.
✓	4. The database will be structured for flexible use, allowing analysts to choose the comprehensiveness of the analysis that they conduct.
	Comments: ✓ Users can selectively decide which fallibilities they continue to analyze, or they can "Select All" for a complete analysis. ✓ Additional queries may increase the flexibility of the analysis.
✓	5. The knowledge base will have the capability to return information to analysts regarding potential human fallibilities and the human factors guidelines relevant to preventing, reducing the probability of, and/or mitigating the effects of these error tendencies.
	Comments: ✓ The database stores all the required information in the Guidelines, and returns it as appropriate when queried. ✓ The information is not differentiated within the Guidelines.
✓	6. Only discrete relationships will be captured in the database. The framework will not include the capability to assess the relative probability, consequence severity, or detectability of potential negative system outcomes.
	Comments: ✓ Discrete relationships between concepts are captured.
✓	7. The software interface will be developed to a functioning level. Enhancements that have the potential to increase the

	sophistication, flexibility, and usability of the tool will be identified but not implemented.
	Comments: ✓ The software interface functions.

KEY	
-	Goal not met
✓	Goal satisfactorily met
+	Goal completely met

Based on the evaluation of the extent to which each goal was met, it is possible to place the HFIRM prototype along each of the dimensions of human performance models established in the Literature Review chapter. Using the vocabulary of these dimensions, the ultimate goal of the HFIRM prototype was to guide users through a cause-oriented, generalizable, prospective, and systematic analysis of a target task in order to support both the identification and remediation of potential errors. Table 21 illustrates the extent to which the HFIRM prototype achieved those goals. As noted in the evaluation of the goals, the primary factor preventing the HFIRM from complete fulfillment of its intended purpose is the lack of structure in the Error Identification and Remediation phase.

Table 21: HFIRM prototype goal-state and actual-state along the Critical Dimensions of Human Performance Models

CRITICAL DIMENSIONS OF HUMAN PERFORMANCE MODELS	
Identification	**Remediation**
● ☆	
The objective of the HFIRM prototype is to support both the identification and remediation of potential human errors. Extending the methodological procedure and augmenting the structure of the Guidelines may improve HFIRM's potential as a remediation tool.	
Effect-oriented	**Cause-oriented**
	✪
HFIRM addresses the conceptual causes of human error by identifying the Human Information Processing stages employed during the task, and addresses the contextual triggers of human error by identifying Necessary Conditions present during the task.	
Domain-specific	**Generalizable**
	✪
The HFIRM methodology is applicable across domains and is supported by a human fallibility database that also contains non-domain specific information.	
Retrospective	**Prospective**
	✪
The HFIRM prototype supports the prospective identification of potential human fallibilities and errors.	
Ad-hoc	**Systematic**
	● ☆
HFIRM guides users through a step-by-step process during which the information necessary for the analysis is drawn from the Human Fallibility Database and displayed to the user. The analysis is less systematic during the Error Identification and Remediation phase, however this phase has the potential to be improved by extending the methodology to include a more rigorous procedure for utilizing the information in the human factors guidelines to identify potential errors.	

KEY	
☆	Target
●	Current state
✪	Target achieved

Analyzing the HFIRM prototype in the context of the critical dimensions of human performance models highlights both the strengths and weaknesses of the methodology. One significant weakness of the methodology is reflected in the disparity between the goal state and current state in the Remediation/ Identification dimension. The objective of the methodology is to support both the identification and remediation of potential errors, however the Usability study responses indicated that analysts were not consistently able to translate human factors guidelines into remediation strategies. The disparity between the target position and current position in the Ad-hoc/ Systematic dimension is also attributable to lack of structure in the Error Identification and Remediation phase, because the methodology does not clearly define the procedure to translate guidelines into remediation strategies. Along the other three dimensions the HFIRM prototype achieves its target position by providing a cause-oriented, generalizable, and prospective analysis methodology.

Analyzing the HFIRM prototype in the context of the critical dimensions of human performance models clarifies the strengths and weaknesses of the methodology. The indications of the critical dimensions analysis are consistent with the goals evaluations presented earlier in this chapter. Based on these analyses, the primary shortcoming of the HFIRM prototype that prevented it from completely fulfilling several goals was lack of structure in Phase 3 (Remediation). The usability of the methodology was most strongly influenced by the limitations of the MS Access platform. Examination of the weaknesses of the HFIRM prototype prompted the identification of multiple opportunities for improvement of the methodology, including integration with FMEA and conversion from MS Access to a more sophisticated technological platform. These development opportunities are revisited in the Future Research and Development section of the next chapter, where they are synthesized and prioritized. Recognition of the strengths of the HFIRM prototype informs discussion in the Conclusions section regarding the contribution the prototype will make to the field of human error analysis.

Conclusions and Future Research

The Conclusions section reviews the research conducted to develop the HFIRM prototype and the results of the development process. The Conclusions section also critically evaluates the contribution of the prototype to the field of human factors. The Future Research and Development section synthesizes and prioritizes development opportunities identified throughout the course of this research for future development cycles.

Conclusions

This section summarizes the objectives, development, evaluation, and achievements of the HFIRM prototype. Additionally, this section considers contributions of the HFIRM prototype relative to other human existing error analysis methods.

Summary

The Literature Review chapter summarized and analyzed important human factors concepts, analysis techniques, and existing human error analysis models. Twenty-four methods for analyzing human error were evaluated based on the Critical Dimension of Human Performance Models. This analysis revealed a need for a systematically-defined and theory-based analysis procedure that uses an information-driven approach to support the prospective identification and remediation of potential human errors. The purpose of this research was to meet this need by developing and testing a prototype framework that supports the practical application of human factors knowledge to the analysis and design of complex systems.

The HFIRM prototype integrates and extends concepts from extant human error analysis techniques and synthesizes human performance knowledge in order to develop a novel human performance analysis methodology. This research had two primary objectives. The first was to define a generalizable analysis procedure that efficiently facilitates the systematic identification of potential errors in a target task.

The second was to support the prospective remediation of potential errors by providing analysts with human factors information relevant to implementing focused intervention strategies.

The strategy employed to achieve the objectives was to develop a methodology that draws on a database of human performance information in order to identify potential human fallibilities. The methodology consists of three phases. The first phase addresses the conceptual level of human error by facilitating the identification of human information processing stages employed during the target task. The second phase addresses the contextual level of human error by supporting the identification of system factors that, if present, make specific human fallibilities possible. The third phase returns the potential human fallibilities to the analysts along with the necessary information to both determine how those human fallibilities may be manifested as human errors and to develop appropriate remediation techniques.

The Human Fallibility Database that supports the consistent and systematic implementation of the methodology synthesizes human performance information from *Engineering Psychology and Human Performance, 3rd Edition* (Wickens and Hollands, 2000). The structural foundation of the database is the Human Fallibility Ontology, which establishes the universe of discourse and defines the concepts, attributes, and relationships within that domain. Together, the methodology and the supporting Human Fallibility Database comprise the Human Fallibility Identification and Remediation Methodology (HFIRM) prototype.

The resulting HFIRM prototype satisfactorily fulfills all of the goals associated with the objectives of this research. Additionally, information gathered during the usability study suggests that participants perceived the HFIRM prototype positively in terms of both its usability and its efficacy. Positive responses to efficacy questions support the face validity of the HFIRM prototype. Feedback from the usability study also provides valuable insights into opportunities for improvement and extension of the prototype.

Contributions

The HFIRM prototype represents significant progress in the area of human error analysis because it integrates a theoretical foundation of human factors information with a rigorous procedure for its practical application to real-world systems. The primary contribution of this research to the field of human factors is the definition of a systematic methodology that draws on a database of human performance information to identify human fallibilities.

The Human Fallibility Database provides the necessary human factors information to conduct an information-driven analysis. Because the methodology draws from a database of human factors information, it consistently provides a principled assessment of the target task. The analysis supports the evaluation of the conceptual, contextual, and behavioral levels of human error that may affect system performance, and provides analysts with human performance information relevant to developing targeted remediation strategies.

The integration of the Human Factors Database into the methodology differentiates the HFIRM prototype from other highly sophisticated human error analysis methods, such as Embrey's (1986) Systematic Human Error Reduction and Prediction Approach (SHERPA). Both SHERPA and the HFIRM prototype are prospective, cause-oriented, generalizable models that address the identification and remediation of human error. Additionally, the methodological procedure used in SHERPA is similar in several respects to the HFIRM prototype. Both SHERPA and the HFIRM prototype utilize task analyses of higher level system goals. HFIRM considers the human information processing stages employed during a task, while SHERPA categorizes tasks by action stages (a concept closely related to human information processing stages).

The ability to draw information from a database of relevant human factors information differentiates the HFIRM prototype from SHERPA. While SHERPA requires analysts to identify possible errors using only task descriptions, the HFIRM prototype provides analysts with potential human fallibilities and human factors guidelines that provide information regarding how and when those fallibilities may be manifested. This information supplements analyst memory, reducing the cognitive burden placed upon analysts during the analysis of complex tasks. By providing information that analysts would otherwise have to produce from memory, the HFIRM prototype also encourages the more consistent and comprehensive use of human factors information during human error analyses.

There is also reason to believe that the HFIRM prototype has the potential to be useful in industrial settings. Significant investments have been made into the development of the HFYI Design CoPilot (Research Integrations, 2008), a prospective design tool that also draws on a database of human factors information. The Design CoPilot differs from the HFIRM prototype because the Design CoPilot is domain-specific (aviation) and is only concerned with improving design. In contrast, the HFIRM prototype is a generalizable methodology that supports both the identification and remediation of human error. The Design CoPilot also operates on a much more sophisticated platform than the HFIRM prototype. As a result the Design CoPilot is easier to navigate and search. Despite their substantial differences, both the HFIRM prototype and the Design CoPilot fill a similar need: they provide analysts with comprehensive human factors information in order to reduce the occurrence and impact of human errors. The heavy investment in the Design CoPilot by the Federal Aviation Administration is a promising indicator that there is a real need in industry for the functions performed by the HFIRM prototype.

This research also produced the Critical Dimension of Human Performance Models. These five continua are identification/ remediation, effect oriented/ cause oriented, domain-specific/ generalizable, retrospective/prospective, and ad-hoc/ systematic. These dimensions are useful for three primary activities. First, they are helpful in distinguishing the purposes and objectives of extant human error analysis models. Secondly, they assist in the evaluation of the strengths and weaknesses of human error analysis models. Additionally, they support the identification of needs that existing methods have not filled, highlighting opportunities for future research. The development of these dimensions and the evaluation of existing human error models using the dimensions represent additional contributions of this research to the field of human error analysis.

The HFIRM prototype provides a strong foundation for future research, and this thesis provides detailed direction for future development. Currently, the HFIRM prototype has been developed to a functioning level. As described in the Future Research and Development section, there is enormous potential for enhancing the tool both by integrating it with a Failure Modes and Effects analysis and by converting it to a more sophisticated web-based application.

Future Research and Development

This section synthesizes the development areas identified through this research and elaborates on the most promising development opportunities. Potential investments that are critical to the central purpose and functions of the HFIRM prototype are prioritized and discussed in the most detail. Augmentations that may enhance the peripheral functions of the HFIRM prototype are also noted. Opportunities for future research include refining the database entity-relationship structure, populating the database with a broader range of information, and increasing the functional sophistication, flexibility, and usability of the software interface. While identifying these development opportunities is included in the scope of this research, implementing them is not.

Proposed prioritization of development opportunities:

1. Convert tool from MS Access to a more sophisticated application
2. Make the basic usability enhancements indicated by the Usability study
3. Incorporate FMEA principles into the Error Identification and Remediation phase and enhance the organizational structure of the Guidelines
4. Mitigate the proliferation of information
5. Expand the content and adjust the language of the database
6. Add queries to increase the flexibility of the database
7. Define specific goals for the task model

These development opportunities are discussed in detail below.

1. Convert tool from MS Access to a more sophisticated application

The MS Access platform significantly constrains both the usability and efficacy of the HFIRM prototype. An immediate opportunity exists to improve the effectiveness of the HFIRM platform by converting it to a more sophisticated platform such as a web-based application. In the words of one usability study participant, “MS Access is a pain.” This improvement should be a high priority because it will facilitate the implementation of numerous other critical enhancements that affect both the usability and efficacy of the tool.

2. Make the basic usability enhancements indicated by the Usability study

After converting the analysis tool from MS Access to a more sophisticated application, several minor usability enhancements that were identified by the Usability study should be implemented. These include the following:

- Develop a “back” functionality that allows users to navigate back to previous steps of the analysis.
- Eliminate the repetitive display of Necessary Conditions by restructuring the query logic and/or the presentation format.
- Improve user understanding of the relationships between Human Information Processing Stages, Necessary Conditions, and the target task by providing examples of commonly associated task types and verbs. The benefit of the additional information needs to be balanced with the detrimental effect of increasing the complexity and risk of information overload.
- Clarify the stage model of human information processing by displaying a spatial diagram of the model that illustrates the relationships between stages (similar to Figure 2).
- Make the “Select All” boxes more salient, and emphasize the conditions under which users should attempt to select specific human fallibilities.

3. Incorporate FMEA principles into the Error Identification and Remediation phase and enhance the organizational structure of the Guidelines

The third major development opportunity is to apply principles of Failure Modes and Effect Analysis (FMEA) to the Error Identification and Remediation phase. This requires both the refinement of the Guidelines concept in the database, and the extension of the methodology procedure. Incorporating elements of FMEA into the analysis is a logical extension of the functions HFIRM already performs. HFIRM and FMEA complement one another because HFIRM supports the identification of potential human fallibilities which can be converted directly into failure modes as part of the FMEA.

Refining the organizational schema may include distinguishing the types of human factors considerations that are presented in the Guidelines. The human factors information that is currently presented as Guidelines during Phase 3 (Remediation) may be differentiated based on the FMEA framework, and presented as relevant to the detectability, severity, probability or effects of potential errors. There is a significant opportunity to position HFIRM as an enhancement to FMEA that promotes the systematic identification of failure modes.

In addition to enhancing the organization of the guidelines, there is an opportunity to incorporate more specific information regarding potential errors. For example, Reason (1987) defines general categories of information processing errors, each of which is linked to a specific human information processing stage. These categories are enumerated in Table 22. Providing users with information regarding the basic error categories that are possible during each human information processing stage may help analysts identify the specific errors that may occur in their system.

Table 22: General categories of information processing errors (Reason, 1987)

Information Processing Errors	**Description**
False Sensations	Lack of correspondence between our subjective experience of the world and objective reality. False sensations occur when aspects of the physical world have been distorted or misrepresented by the sensory apparatus.
Misperceptions	Erroneous interpretations placed upon sensory data
Attentional Failures	Inappropriate allocation of the control resources which initiate and guide mental activities
Memory Lapses	Failures of short-term memory including forgetting intentions, decisions, and previous actions
Inaccurate or blocked recall	Failure of long-term memory during recollection
Decision-Making Errors	Misjudgments and reasoning errors representing deviations from rational thought that result in a failure to form the correct intentions; mistakes
Unintended word or actions	Unintended deviations of actions from the intended path; slips

4. Mitigate the proliferation of information

A fourth high-priority improvement opportunity is to mitigate the proliferation of information that occurs during an analysis. One strategy for accomplishing this is to limit the complexity of tasks by constraining the number of human information processing stages that a single task can employ. This requires strictly defining the meaning of “task” for the purposes of the analysis. To prevent confusion between characteristic of the task and of the system, additional emphasis should be placed on the importance of clearly defining the boundaries of the task and its relationship to the larger system. Once defined, the analysis tool should emphasize and reiterate that the focus of the analysis is the target task. Utilizing fuzzy ontology principles may also improve the ability of the database to capture levels of relatedness between concepts in the Human Fallibility Ontology.

An alternative approach to reducing information proliferation is to provide users with additional opportunities to filter large quantities of information by responding to relatively simple prompts. Currently each phase in the analysis process filters information according to its relevance to the target task. During each phase irrelevant information is eliminated, and potentially relevant information is returned to the user for further filtering. Incorporating another carefully chosen analysis phase has the potential to further reduce the quantity of information analysts must consider.

5. Expand the content and adjust the language of the database

An additional opportunity for improvement is to expand the database content and reduce the technicality of the database language. Currently the database employs highly technical human factors vocabulary. Using language that requires less technical expertise to comprehend may increase the ease of use for both human factors experts and system experts.

The human performance analysis is only as thorough as the content stored in the supporting human performance database. Currently the human performance database content is limited to the information extracted from *Engineering Psychology and Human Performance, 3rd Edition* (Wickens and Hollands, 2000). Key subject areas that are not covered extensively by that text include communication, team tasks, sensory registration, and action control. Adding these underrepresented subject areas to the database has the potential to improve the accuracy and validity of the database output.

In order to develop a truly comprehensive human performance database, information from a variety of sources and contributors will need to be synthesized. The collaborative ontology development environment introduced by Bao et al. (2006) may contribute to the effective integration of data from diverse sources. Their framework utilizes the concept of ontology modulation to support partial editing, information sharing, and data integration in broad and data-rich domains of interest. A second valuable source of guidance for developing generalizable ontologies is Bernaras et al.’s (1996) modular approach, which facilitates the modeling of complex real-world domains while preserving the relationships between system concepts.

6. Add queries to increase the flexibility of the database

After the critical enhancements are made to HFIRM, the sophistication of the tool may be further enhanced by developing additional queries that increase the flexibility of the database. Potential functionality includes search capabilities and advanced options that allow users to customize the analyses that they perform. The HFYI Design CoPilot (Research Integrations, 2008) provides an excellent example of a web-based application that allows users to search a database of information in several different ways.

7. Define specific goals for the task model

The final development opportunity identified during this research is to define specific requirements for the information that must be captured as an integral part of the task model. HFIRM prompts users for information regarding human information processing stages and characteristics of the task, operator, and environment (which constitute Necessary Conditions). Requiring that these system factors be explicitly represented in the task model has the potential to both expedite the analysis and increase its thoroughness and consistency. For example, if a system is represented in an IDEF0 model, requirements could be created that mandate that information regarding the situational factors and human information processing stages employed are captured in the IDEF0 model mechanisms and controls.

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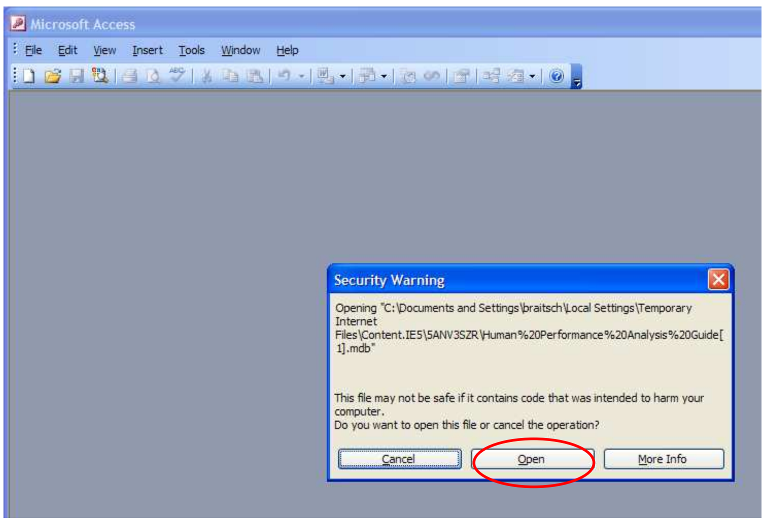
Appendices

Appendix A: User procedure

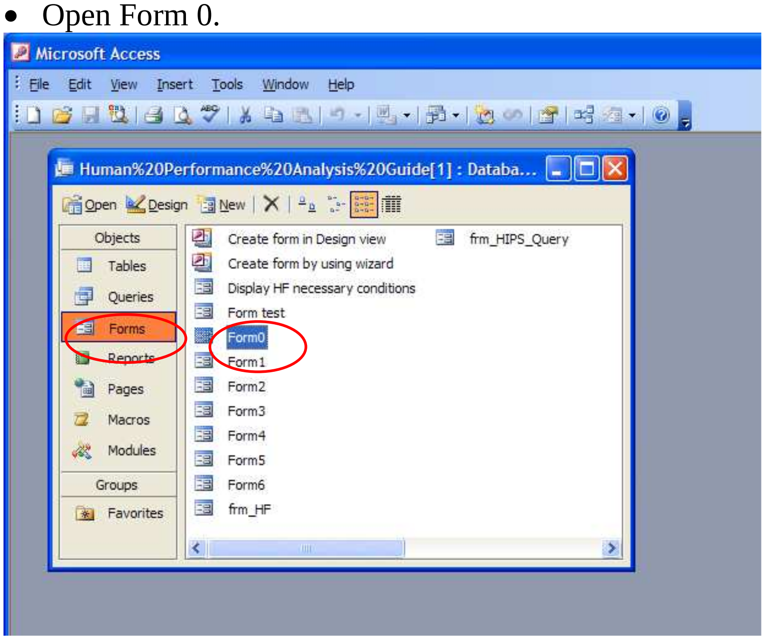
This appendix provides step-by-step instructions intended to guide users through the successful implementation of the HFIRM supported by the Human Fallibility Database.

<u>Get Started</u>

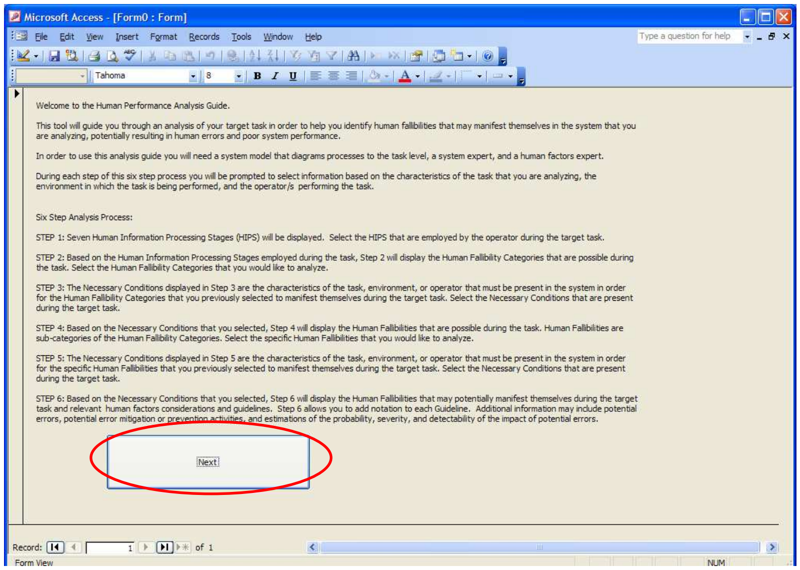
- Open the Human Performance Analysis Guide file in Microsoft Access.
- If a Security Warning appears, select "Open."



- Select "Forms" from the Objects menu.
- Open Form 0.

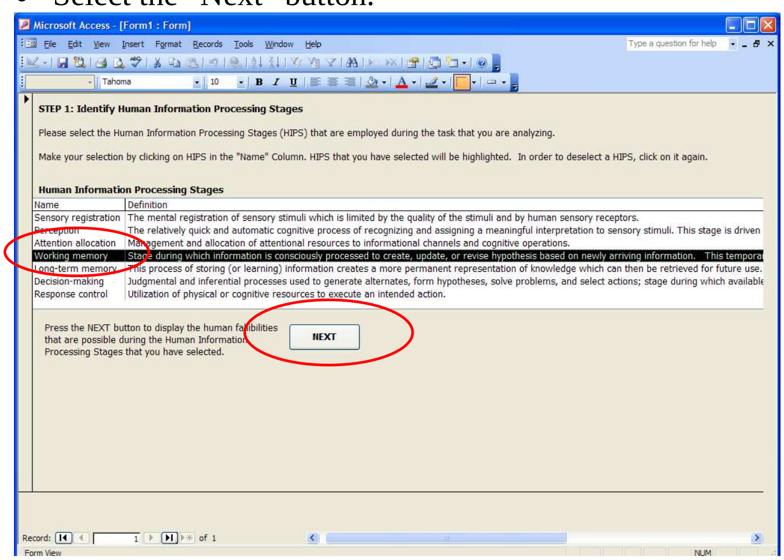


- Read the introduction. Select the “Next” button.



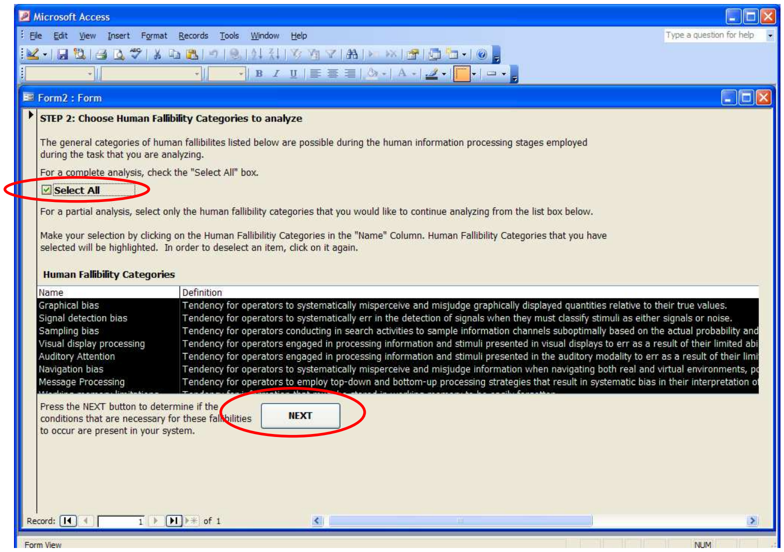
Step 1

- Select the Human Information Processing stages.
- Select the “Next” button.



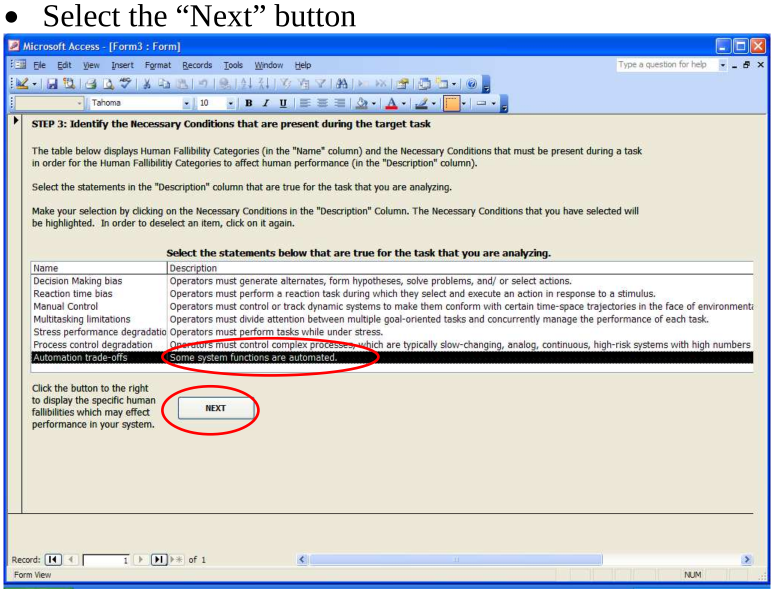
Step 2

- "Select All" or choose specific Human Fallibility Categories to analyze
- Select the "Next" button



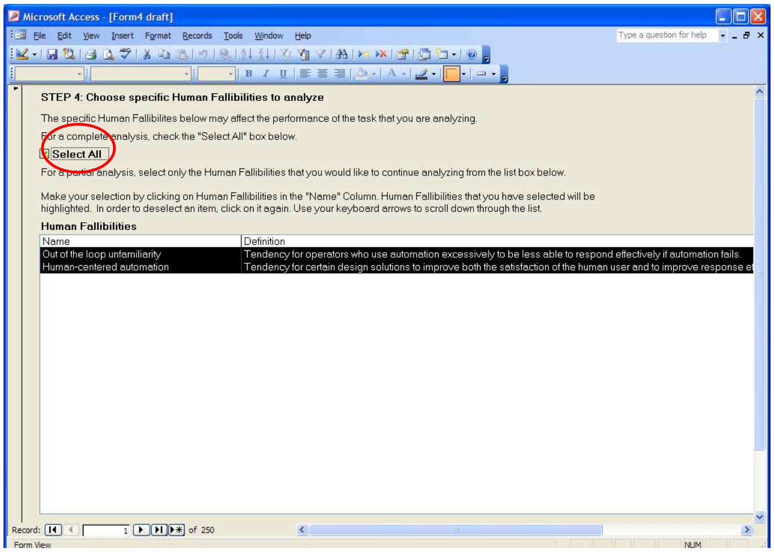
Step 3

- Select Necessary Conditions from the right column
- Select the "Next" button



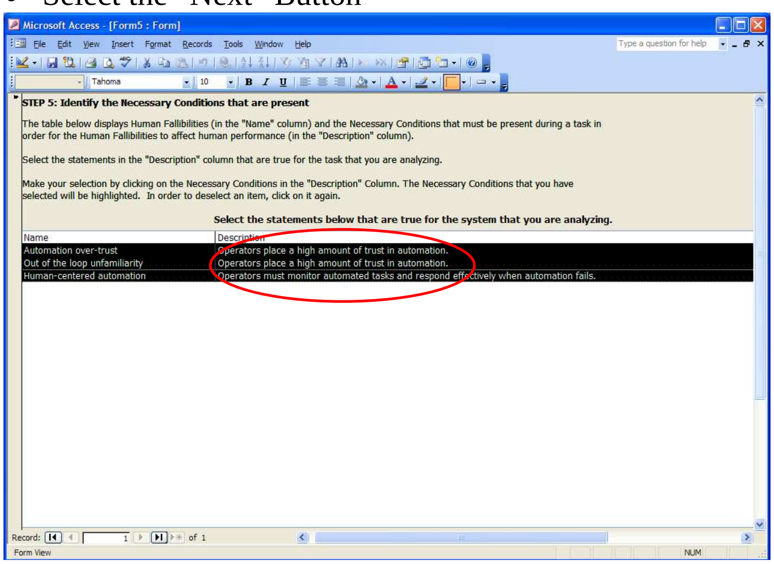
Step 4

- "Select All" or choose specific Human Fallibilities to analyze
- Select the "Next" button

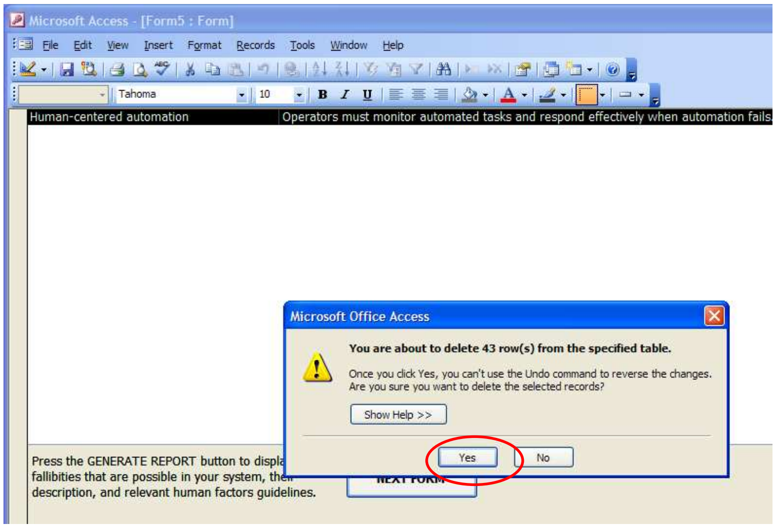


Step 5

- Select Necessary Conditions from the right column
- Select the "Next" Button

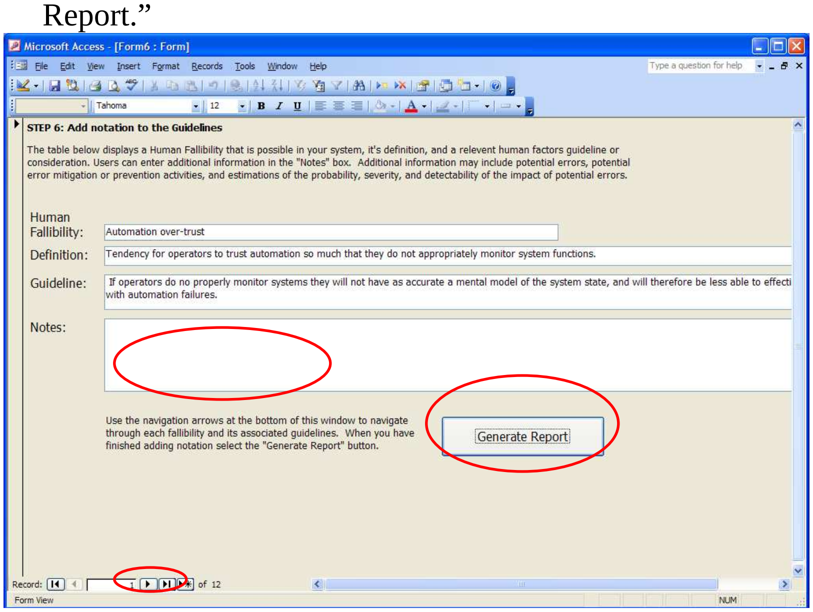


- After you select the “Next” button, two warning pop-up boxes will appear. Select “Yes” for both.

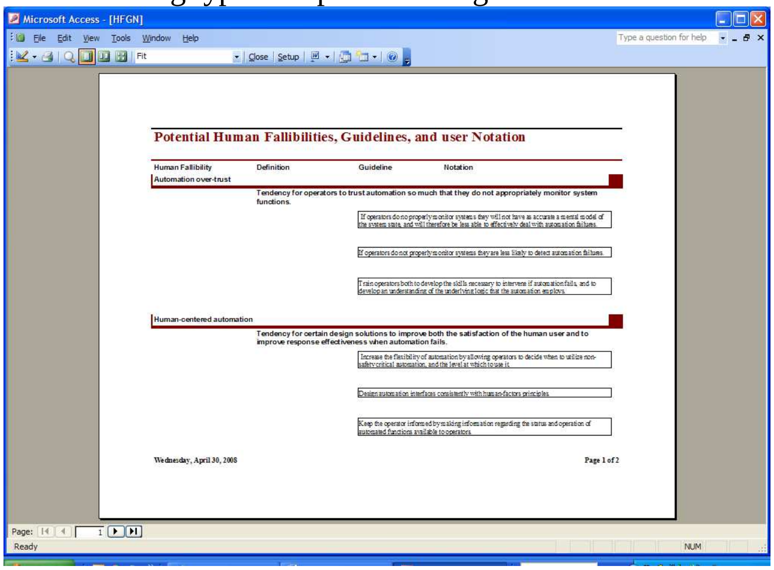


Step 6

- Add notation to guidelines as desired.
- Use the arrows at the bottom of the screen to navigate through each fallibility and its associated guidelines.
- When you have finished adding notation to all the guidelines, select “Generate Report.”



- The following type of report will be generated:



Appendix B: Protocol for Initial Application

Protocol for Initial Application

Project Title: A human factors analysis tool to support the identification of potential human fallibilities in complex systems
Principal Investigator: Dr. Kenneth Funk, Industrial and Manufacturing Engineering
Co-Investigator: Leslie Braitsch, Industrial and Manufacturing Engineering
Study Number: 3937

1. Brief Description

The objective of this study is to generate information on the usability and usefulness of a computer-based human factors analysis tool. The analysis tool being tested is part of the thesis research being conducted by Leslie Braitsch, a graduate student in the Department of Industrial and Manufacturing Engineering Department. The intended use of this research is to capture user feedback in order to improve the analysis tool.

2. Background and Significance

The objective of this research is to prevent human error by supporting the practical application of human factors information to the analysis and design of complex systems. This is accomplished through the development of a human performance database which organizes and synthesizes existing human factors information. The fallibility analysis consists of a defined action sequence for performing a knowledge-driven examination of a target system, providing for the practical application of human factors principles to real-world systems. The result is a prototype Human Fallibility Identification Tool (HFIT).

3. Methods and Procedures

Participants will be recruited from the Spring 2008 IE 546 class. Students who are minors will be requested not to participate. As part of a course assignment, students will be required to conduct human factors analyses both unaided and using the human factors analysis tool of their choice. During the IE 546 course students will be taught how to conduct human factors analyses and will learn about several existing analysis tools, including the Human Fallibility Identification Tool (HFIT). The research project will be explained to students before they decide which human factors analysis tool to use during the assignment. The verbal script for explaining the purpose of the study and recruiting participants is outlined in Appendix A.

Participation in this study will not be a required portion of any course. Participants will be recruited from the students who choose to use HFIT to conduct their aided analyses. Those students who choose to complete the survey will receive extra credit equivalent to 4% of their final grade. Students who choose not to participate in the study will be able to earn an equal amount of extra credit (4%) by completing the assignment described in Appendix D. Both the study and the alternate project will take about 15-20 minutes to complete.

Before beginning the survey, participants will be asked to read and sign a consent form (see Appendix B). This informed consent document will indicate that participation is completely voluntary, the risk/ benefits of participation, the purpose of the study, and that participants can withdraw at any time without loss of benefits. Participants will be permitted to ask questions at any time. Students who wish to withdraw from the study before completing the questionnaire will not receive extra credit for participating, however they will still have the option to complete the alternate project to earn 4% extra credit.

4. Risk/Benefit Assessment

- Risks: There are no discernible risks to the participants as they are asked only to complete a paper survey regarding their experience with a computer-based task analysis tool.

- Benefits: The results of the study will help guide the further development of the Human Fallibility Identification Tool, which helps system analysts anticipate and prevent human errors. Participants may not benefit directly from the study.

- Conclusions: As there are no foreseeable risks to participants, and the benefits may include contributing to the reduction of human error, we conclude that the potential benefits of this study significantly outweigh the risks.

5. Participant Population

The participants for this study will be students in the Spring 2008 IE 546 course at Oregon State University. The participant population is restricted to adults 18 years of age and older. The participant population is not restricted by gender or ethnic group. The number of participants will not exceed twenty.

6. Subject Identification and Recruitment

Students will be recruited through an invitation in the Spring 2008 IE 546 Oregon State University course. All IE 546 participants who are at least 18 years old are eligible to participate.

7. Compensation

Students will receive extra credit for participation equal to 4% of their final IE 546 grade. Students can choose to earn an equal amount of extra credit (4% of their final grade) by completing an alternative project that will take an equivalent amount of time (15-20 minutes) as participating in the study (see Appendix D).

Participants will be free to withdraw from the experiment at any time and will be informed of this prior to participation. Students who choose to withdraw from the study before completing the questionnaire will not receive extra credit. However, they will still have the option to complete the alternate project (see Appendix D) for extra credit.

8. Informed Consent

Participants will be provided with an informed consent form (see Appendix B) and will be permitted to ask questions prior to making a decision on whether to participate. The informed consent form explains that participation is voluntary, the risks/ benefits of participation, the purpose of the study, and that participants may withdraw at any time without loss of benefits. If they would like to volunteer for the study, participants will be asked to sign the form to indicate their informed consent and return it to the co-investigator.

9. Anonymity or Confidentiality

The informed consent form includes a statement that indicates, “your responses will be protected to the extent permitted by law.” No individual names or other personal identifying information will be included on the survey. Informed consent signatures will not be filed with the questionnaires to ensure anonymity. No personal information will be collected, and results will be published in group form only.

Appendix C: Informed Consent Form

Informed Consent Form

Project Title:	A human factors analysis tool to support the identification of potential human fallibilities in complex systems
Principal Investigator:	Dr. Kenneth Funk, Industrial and Manufacturing Engineering
Co-Investigator:	Leslie Braitsch, Industrial and Manufacturing Engineering
Study Number:	3937

WHAT IS THE PURPOSE OF THIS STUDY?

You are being invited to take part in a research study designed to assess the usability and effectiveness of the Human Fallibility Identification Tool, which helps analysts identify potential system errors. The results of this study will help guide the further development of the human factors analysis tool.

WHAT IS THE PURPOSE OF THIS FORM?

This consent form provides you with the information you need to decide whether or not to participate in the study. Please read the form carefully. You may ask any questions about the research, the possible risks and benefits, your rights as a volunteer, and anything else that is not clear. When all of your questions have been answered, you may decide if you would like to participate in the study.

WHY AM I BEING INVITED TO TAKE PART IN THIS STUDY?

You are being invited to take part in this study because you are taking the Spring 2008 IE 546 course, during which you will analyze tasks using human factors analysis tools.

WHAT WILL HAPPEN DURING THIS STUDY AND HOW LONG WILL IT TAKE?

During this study you will be asked to complete a survey regarding your experience with the Human Fallibility Identification Tool. The survey is expected to take 15-20 minutes to complete.

WHAT ARE THE RISKS OF THIS STUDY?

There are no foreseeable risks to participating.

WHAT ARE THE BENEFITS OF THIS STUDY?

You may not benefit directly from being in this study. However, the results of this study will help guide the further development of the Human Fallibility Identification Tool.

WILL I BE PAID FOR PARTICIPATING?

You will not be paid for participating in this study, however you will earn extra credit equal to 4 % of your final grade. If you do not wish to participate in this study, you can earn an equivalent amount of extra credit (4%) by completing the alternative extra credit project.

WHO WILL SEE THE INFORMATION I GIVE?

The information you provide during this research study will be kept confidential to the extent permitted by law. You will not be asked to provide any personal information during this research. If the data collected in this research project is published, your name will not be associated with the information. Your data will be coded according to arbitrarily assigned numbers and stored within computer files. Only the principal investigator and experimenters have access to this data.

DO I HAVE A CHOICE TO BE IN THE STUDY?

Participation in this study is fully voluntary. If you decide to take part in the study, it should be because you want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You will not be treated differently if you decide to stop taking part in the study.

If you decide to volunteer for the study, you can stop at any time during the study and still keep the benefits and rights you had before volunteering. If you choose to withdraw from this study before completing the survey your data will not be included in the final analysis. If you choose to withdraw before completing the survey you will not receive extra credit for participating in the study. However, you will still have the option to complete the alternate extra credit project.

WHAT IF I HAVE QUESTIONS?

If you have any questions about this research project, please contact: Leslie Braitsch (Student Researcher, braitscl@engr.orst.edu) or Kenneth Funk (Principle Investigator, funkk@engr.orst.edu). If you have questions about your rights as a participant, please contact Oregon State University Institutional Review Board (IRB) Human Protection Administration at (541) 737-4933 or by e-mail at irb@oregonstate.edu.

By signing below you are indicating that this research study was explained to you, that your questions have been answered, and that you agree to take part in this study.

Name____

Date___________

Appendix D: Usability Study questionnaire

Human Fallibility Identification Tool Questionnaire Date: Participant ID:

Project Title: A human factors analysis tool to support the identification of potential human fallibilities in complex systems

Principal Investigator: Dr. Kenneth Funk, Industrial and Manufacturing Engineering

Co-Investigator: Leslie Braitsch, Industrial and Manufacturing Engineering

<u>Please answer the following questions based on your experience using the Human Fallibility Identification Tool.</u>

1.What is your level of human factors or engineering psychology training? Please circle the appropriate response:

  a.None before this course
  b.Basic introduction during a previous course
  c.Previous completion of a course dedicated to either human factors or engineering psychology.

2.Did you use the human factors analysis tool during your first or second analysis? Please circle the appropriate response:

  a.First analysis
  b.Second analysis

3.How long did it take you to analyze the task using the tool?

4.How long did it take you to analyze the task when you did not use the analysis tool?

5.How many potential errors did you identify using the analysis tool?

6.How many potential errors did you identify when you did not use the analysis tool?

7.Please list the three greatest strengths of the analysis tool.

  a.
  b.
  c.

8.Please list the three greatest weaknesses of the analysis tool.

  a.
  b.
  c.

9.Please list your three top recommendations for improving the analysis tool.

  a.
  b.
  c.

10.Do you have any other comments or suggestions concerning the tool?

Please indicate your level of agreement with each of the following statements by circling the appropriate response on a scale of 1 to 5.

	Strongly Agree	Some-what Agree	Neutral	Some-what Disagree	Strongly Disagree
The instructions on each page were clear and easy to understand.	1	2	3	4	5
I was able to navigate through the pages without difficulty.	1	2	3	4	5
I understood the purpose of each step in the process.	1	2	3	4	5
The definitions and descriptions on each page helped me make the correct selections.	1	2	3	4	5
It was clear to me how to select items from the list boxes.	1	2	3	4	5
It was clear to me where I needed to click in order to progress to the next page in the process.	1	2	3	4	5
Headings and buttons were clearly labeled.	1	2	3	4	5
The pages were easy to read.	1	2	3	4	5
I was able to confidently determine which Human Information Processing stages were employed during the target task.	1	2	3	4	5
I was able to confidently determine which Necessary Conditions were present during the target task.	1	2	3	4	5
The quantity of information that I had to choose from on each page was reasonable.	1	2	3	4	5
The analysis tool identified potential human fallibilities that I would not have identified without the tool.	1	2	3	4	5
The potential Human Fallibilities returned by the analysis helped me identify potential human errors.	1	2	3	4	5
The Human Factors Guidelines returned by the analysis helped me determine the probability and severity of the threat posed to the system.	1	2	3	4	5
The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes.	1	2	3	4	5
Conducting the analysis using the analysis tool yielded more *thorough* results than conducting the analysis unaided.	1	2	3	4	5
Conducting the analysis using the analysis tool yielded more *valuable* results than conducting the analysis unaided.	1	2	3	4	5
Using the analysis tool increased the effectiveness of my analysis.	1	2	3	4	5
I preferred conducting the analysis with the tool, as opposed to without it.	1	2	3	4	5
I will choose to use the tool the next time I conduct a human factors analysis, if it is available.	1	2	3	4	5

Appendix E: Complete Usability Study questionnaire responses by participant

Appendix Table 1: Complete participant responses to introductory questions

Participant ID	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Level of Human Factors Eng. Training*	C	C	B	B	B	A	B
Time to analyze task using HFIRM (mins)	45	30	45	90	5	15	35
Time to analyze task without using HFIRM (mins)	30	60+	45+	120+	35	45	60
Number of potential errors identified using HFIRM	15	210	13	N/A	13	79	6
Number of potential errors identified without HFIRM	10	35	6	N/A	1	30	3

*A= None before this course, B= Basic introduction during a previous course, C= Previous completion of a course dedicated to either human factors or engineering psychology.

Subject ID	#1	#2	#3	#4	#5	#6	#7
Strengths	Inclusiveness Standardized format Flexibility	Fast and easy Good database on human factors analysis for future research Gives accurate feedback on the task when concerning human factors	Easy to use Very clear Provides really good human fallibilities	Breaking down the human fallibilities to maximum extent Diversified examinations/ analysis of factor Reduces my workload	Simple easy interface User friendly Analysis is complete in a few steps	Simply the process of finding errors Help to find more errors Save time	H-F database It facilitates more info to get incorporated into the System Vulnerability Analysis Relatively easy to use
Weaknesses	Information Overload Time consumed to get anywhere Software requirements	Too many repeats Some definitions were difficult to understand or cut off Hard to factor some human factors to our project because of the broad definition	No back button Too much reading	Manual checking for requirements Necessity to generate report Fallibility repetitions	Time consuming No back button Multiple redundancies in terms of explanation need to be manually chosen	Too much reading So many choices	No undo button Couldn't adjust selection screen sizes Microsoft Access is a pain Some descriptions of the human fallibilities were unclear
Recommendations	Increase selectivity If it could be made its own executable program, that would be handy	Maybe separate the definitions a little More organized (group the same categories together) Have a "back" button for rechecking and fix mistakes	Back button When selecting option: When there are identical options it should only show up once.	Repetitions can be avoided (if possible) Information overlap should be fixed Software can be updated to fix above	Please include back button Eliminate Redundancies Make it a stand alone application, like a web interface	Easy to save as a PDF or MS-word format After finished some forms, I hope to only finish several choices in the following forms	Make human fallibilities more clear Add undo button Make selection screens adjustable

Appendix Table 2: Complete participant response to qualitative questions

Participant ID	#1	#2	#3	#4	#5	#6	#7
The instructions on each page were clear and easy to understand.	3	1	1	1	1	1	3
I was able to navigate through the pages without difficulty.	2	1	2	1	1	1	2
I understood the purpose of each step in the process.	2	2	2	1	1	1	2
The definitions and descriptions on each page helped me make the correct selections.	2	2	2	1	3	2	2
It was clear to me how to select items from the list boxes.	2	1	2	1	1	2	2
It was clear to me where I needed to click in order to progress to the next page in the process.	2	1	1	1	1	2	2
Headings and buttons were clearly labeled.	2	1	2	1	1	1	2
The pages were easy to read.	2	2	2	1	1	1	2
I was able to confidently determine which Human Information Processing stages were employed during the target task.	3	2	2	1	3	2	3
I was able to confidently determine which Necessary Conditions were present during the target task.	2	2	2	2	3	1	2
The quantity of information that I had to choose from on each page was reasonable.	4	1	3	3	1	1	4
The analysis tool identified potential human fallibilities that I would not have identified without the tool.	1	1	1	1	1	1	1
The potential Human Fallibilities returned by the analysis helped me identify potential human errors.	2	1	2	1	1	1	2
The Human Factors Guidelines returned by the analysis helped me determine the probability and severity of the threat posed to the system.	2	1	1	2	1	1	2
The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes.	2	1	2	2	1	1	2
Conducting the analysis using the analysis tool yielded more *thorough* results than conducting the analysis unaided.	1	1	2	1	1	1	1
Conducting the analysis using the analysis tool yielded more *valuable* results than conducting the analysis unaided.	2	1	2	1	1	1	2
Using the analysis tool increased the effectiveness of my analysis.	2	1	1	1	1	1	2
I preferred conducting the analysis with the tool, as opposed to without it.	2	1	1	1	1	1	2
I will choose to use the tool the next time I conduct a human factors analysis, if it is available.	2	1	2	1	1	1	2

Appendix Table 3: Complete participant responses to quantitative questions

Appendix F: Usability Study quantitative question summary statistics

Appendix Table 4: Usability Study quantitative question summary statistics

Question	Min	q1	q3	Max	Med.	Mean
The instructions on each page were clear.	1	1	1.5	3	1	1.43
I was able to navigate through the pages without difficulty.	1	1	2	2	1	1.43
I understood the purpose of each step in the process.	1	1	2	2	2	1.57
The definitions and descriptions on each page helped me make the correct selections.	1	2	2	3	2	2.00
It was clear to me how to select items from the list boxes.	1	1	2	4	2	1.86
It was clear to me where I needed to click in order to progress to the next page in the process.	1	1	2	4	1	1.71
Headings and buttons were clearly labeled.	1	1	2	2	1	1.43
The pages were easy to read.	1	1	2	2	1	1.43
I was able to confidently determine which Human Information Processing stages were employed during the target task.	1	2	3	3	2	2.29
I was able to confidently determine which Necessary Conditions were present during the target task.	1	2	2.5	3	2	2.14
The quantity of information that I had to choose from on each page was reasonable.	1	1	3	4	3	2.29
Usability Question Mean						**1.78**
The analysis identified potential human fallibilities that I would not have identified without the tool.	1	1	1	1	1	1.00
The potential Human Fallibilities returned by the analysis helped me identify potential human errors.	1	1	1.5	2	1	1.29
The Human Factors Guidelines returned by the analysis helped me determine the probability and severity of the threat posed to the system.	1	1	2	3	1	1.57
The Human Factors Guidelines returned by the analysis provided valuable information regarding how to reduce the probability and/or mitigate the effects of potential negative system outcomes.	1	1	2	3	2	1.71
Conducting the analysis using the analysis tool yielded more thorough results than conducting the analysis unaided.	1	1	1	2	1	1.14
Conducting the analysis using the analysis tool yielded more valuable results than conducting the analysis unaided.	1	1	1.5	2	1	1.29
Using the analysis tool increased the effectiveness of my analysis.	1	1	1	2	1	1.14
I preferred conducting the analysis with the tool, as opposed to without it.	1	1	1	2	1	1.14
I will choose to use the tool the next time I conduct a human factors analysis, if available.	1	1	1.5	2	1	1.29
Efficacy Question Mean						**1.39**

Appendix G: Usability Study complete participant qualitative responses by category

	Content	Method	Format/ Interface	Efficacy / Functionality
Strengths	Inclusiveness Good database on human factors analysis for future research Very clear H-F database	Flexibility Breaking down the human fallibilities to maximum extent Diversified examinations/ analysis of factor Analysis is complete in a few steps	Standardized format Simple easy interface Easy to use Relatively easy to use User friendly	Gives accurate feedback on the task when concerning human factors Fast and easy Provides really good human fallibilities Reduces my workload Simply the process of finding errors Help to find more errors Save time It facilitates more info to get incorporated into the System Vulnerability Analysis
Weaknesses	Some definitions were difficult to understand or cut off Hard to factor some human factors to our project because of the broad definition Some descriptions of the human fallibilities were unclear	Information Overload Too much reading Manual checking for requirements Too much reading So many choices	Software requirements Too many repeats Necessity to generate report Fallibility repetitions Multiple redundancies in terms of explanation need to be manually chosen Couldn't adjust selection screen sizes Microsoft Access is a pain	Time consumed to get anywhere No back button Time consuming No back button No undo button
Recommendations	Make human fallibilities more clear Information overlap should be fixed Eliminate Redundancies	If selectivity could be increased in some fashion, that would be useful After finished some forms, I hope to only finish several choices in the following forms	Make its own executable program. Maybe separate the definitions a little More organized (group the same categories together) When selecting option: when there are identical options it should only show up once. Repetitions can be avoided (if possible) Make selection screens adjustable	Have a "back" button for rechecking and fix mistakes Back button Please include back button Easy to save as a PDF or MS-word format Add undo button Make it a stand alone application, like a web interface

Appendix Table 5: Complete participant qualitative responses by category