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AVIATION TECHNOLOGIES AND HUMAN ERROR: A RESEARCH LITERATURE DATABASE AND ANALYSIS

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Technological interventions are commonly introduced in aviation to prevent or mitigate human errors. Such interventions, however, may also create new opportunities for error and even result in new error types. To examine the relationship between human errors and technological 'fixes', a research literature database was created that links them together within a three-dimensional matrix, with axes for the human operator, the task, and the environment. Each of these axes, as well as the errors and technologies included in the database, are furthermore organized according to specific taxonomies. To allow for universal access to the database as well as to facilitate widely distributed contributions to its content, the database was published on the World Wide Web via a specifically designed interface. In this paper we describe the development of the web interface and evaluate the usability of the database, including both data entry and query functions.

Introduction

One of the main factors in all aviation accidents is human error. Traditionally, human error in aviation and other complex systems has been addressed by technological 'fixes', either to eliminate the occurrence of errors altogether or by seeking to reduce the negative consequences of errors. Technological interventions, however, add to the complexity of systems in general and may interact with other system components in unforeseeable ways. They may also introduce new error opportunities or even induce different types of errors. Consequently, there is a need to develop standards for evaluating the potential safety benefit of each of these intervention products so that resources can be effectively invested to produce the biggest benefit to flight safety as well as to mitigate any adverse ramifications. Towards this end, a literature database was created to map intervention technologies onto human error categories (Rantanen, Palmer, Wiegmann, & Musiorski, 2006). The underlying framework of the database consists of a three-dimensional matrix with axes for the human operator, the task, and the environment. Human errors and technologies cohabit molecules in the matrix linking them together. The database may be searched through any of the five axes for technologies and errors pertaining to given tasks, task environments, or human characteristics.

The aforementioned database was populated with citations of research on human error associated with specific aviation technologies, gathered from the open literature. As the database allowed for a directed literature search and review of both empirical and theoretical research, the direction of the impact of a given technology and its application on human error (i.e., a cause of an error or a remedy for an error) and

the particular mechanisms of such relationships could be evaluated. Complete evaluation of the database is naturally dependent on population of the database with an exhaustive literature search and review, but some early results and their implications can nevertheless be discussed. We also suggest ways that specialized database applications can be used to guide human factors research on a wide variety of emerging aviation technologies.

In the current database initial query choices draw from existing terms. As the database in time grows, the taxonomies along each axis will need to be re-evaluated and possibly rebuilt based on user-submitted terms. As one of the goals of this project was to develop complete taxonomies for areas in this field, the taxonomies should reflect all possible terms, not just what has already been studied. Towards this end, the database was put on line with a web interface for both querying and entering data (i.e., research literature citations). The interface hence allows for widely distributed data entry for a rapid growth of the database, but more importantly, also for collection of keywords and terms associated with the five axes in the database structure. The latter will facilitate continual taxonomic development in the area of human-technology interaction as new technologies become available and the role and tasks of humans in complex technological systems change.

The original design of the database, as described in Rantanen et al. (2006), brought together citations of published studies relevant to the topic (i.e., human errors and technological interventions) classified into a five-dimensional taxonomy. The database structure, upload (data entry) interface, and search interface were prototyped to make the concept functional and to test its validity. In this paper we describe the sec-

ond iteration of interface development, with a special emphasis on usability, and publication of the database on the World Wide Web for universal access as well as widely distributed contributions to the database content.

Database Design

The database structure, data entry and search programs developed for the web were modified greatly from the original implementation. Database design is customarily done by desired outputs; however, considerations of commonly tedious and time-consuming data input also must be included in specification of database design. In this section we will discuss output features and their implications of data search, data entry features, and finally illustrate the underlying structure of the database with a close look at the query design.

Taxonomies for the Database Dimensions

Selection of taxonomies for each of the database dimensions was done after an exhaustive literature review of applicable systems (see Rantanen et al., 2006, for details). For the task dimension, a taxonomy was created by modifying the system described by Berliner, Angell, and Shearer (1964); this system classified tasks according to human information processing characteristics (e.g., perception, problem-solving, and decision-making) and used descriptive verbs for each category (e.g., detects, inspects, interpolates, etc.). The second dimension, or axis, contains the human taxonomy, which is based on a composite framework depicting human information processing in the form of sequential stages (Wickens, 1984). This framework is in turn based on a number of similar models proposed by different investigators (e.g., Broadbent, 1958; Smith, 1968; Sternberg, 1969; Welford, 1976). For the third axis, Chambers' (1969) detailed and comprehensive example of the environmental variables of consideration was adopted in its entirety, but also expanded by another major subclass, that of task environment.

The above three axes form the basic 3D space for the database organization. As was mentioned before, both human errors and technological applications share a molecule in this space, and each has also its own taxonomy. For the human error taxonomy, the human factors analysis and classification system (HFACS; Wiegmann & Shappell, 2003) was selected; HFACS is based upon Reason's (1990) model of latent and active failures. The technology taxonomy was generated using the list of 48 technologies provided by NASA Aviation Safety Program (AvSP)

and initially classified into seven broad categories: accident mitigation, aviation system modeling and monitoring system, single aircraft accident prevention, synthetic vision systems, system-wide accident prevention, weather accident prevention, and aircraft icing. This taxonomy, however, proved to be wholly inadequate for the purposes of the database. We will detail the reasons for this and our solution below.

Output: The Search Function

The original database had a search function limited to the five dimensions specified by their respective taxonomies. A keyword or phrase in the title plus an author keyword was added in the present application for quick and easy management of the database contents. Topic searches in the original design were chosen from a hierarchy of dropdowns. Once one level was chosen (e.g., 'human') the next level of dropdowns were exposed (e.g., sensing, perception, etc.) In the current implementation all available subtopics are shown, with indentation depicting the next level.

When topics are chosen they appear in a repeater labeled 'selected topics' so the researcher does not have to remember his choices when searching a multiple topic criteria. At the bottom of the page, out of sight in most rectangular browsers (scroll down to see it) is a 'textbox' with the database IDs of the topics separated by commas. This style of building the search criteria allows javascript to process the accumulation the topics. Javascript runs within the browser on the user's computer and updates to page elements such as the 'selected topics' textbox, are immediate. This use of 'client-side' javascript contrasts with 'server-side' page updates which require the reposting of the whole page. When a user finally submits the search, the database query is done server-side where the database resides. Matching article queries are done for all subtopics of the chosen topic or subtopic. A combinatorial analysis is accomplished on all topics or subtopics to produce a set of combinations to be submitted to an analysis of matching articles.

If a user chooses a title keyword or phrase or an author keyword as part of the query criteria, it is not necessary to enter a whole word. Structured query language (SQL) used in this database application includes a command for comparison, which looks for any instances of a phrase within the whole character string of a database field. Also, the default SQL search is not case sensitive; 'wick' entered in the author field will return 'Wickens' as well as 'Artwick', if there was such an author, and 'disp' entered in the title field will find instances of 'display' in the title.

Once a query is submitted to the server, all textboxes on the page are cleared for the next query. The title keyword, author keyword and topics selections are repeated above the query results. In addition to standard citation information and links to online articles, all topics associated with each article are displayed.

Input: Publications Entry and Topics Assignment.

The original design of the database utilized separate tables for journal names and author names. Journal choices were deemed finite enough to leave in their own table, which loaded the journal dropdown. Journals titles may be added on the same page as the publications entry and topics assignment function in order to expedite the entry process. Author names are entered by typing into textboxes. Upon submission of the article authors' names are combined into one field in the article table and are extracted when needed to display the authors in the search findings.

During the testing of the publication entry function the technology dimension of the five-dimensional taxonomy system proved problematic for the reason that very few published articles that made sufficiently unambiguous references to the NASA AvSP technologies were found. Thus another, 'sixth' dimension was added, within which additional technologies could be entered into the database. These dimensions were later combined into an expanded technology category. Topic/sub-topic hierarchies may be assigned to these technologies later, as long as the table ID is not disturbed. Multiple technology structures may be added relatively easily at any time that database needs to be applied in new research areas. The same is true also for other dimensions in the Five-Dimensional Taxonomy system as long as another field is added to the topics table to allow a new dimension to relate to the original five.

Given inevitable, and indeed desirable and expected, changes to topic dimensions, the program code driving the topic selection dropdowns was stripped from applicable pages and placed in a common file where changes can be reflected in all pages that use the dropdown. The topic dropdowns themselves could be optionally displayed, allowing more versatility of the database, but such technology has yet to be incorporated.

Browsing the Database: The Browser Function

During the development of web-based, data-driven concept, the data that have been entered must frequently be reviewed and edited. A browser function will allow for this. A simple delete function is also part of the current browser.

The Database

The following tables and relevant fields are used in the database:

Table: tblarticles, (the Articles table)

Fields: intartid (article ID), txttitle (title), abstract, pubyear (publication year), intvolume (volume number), intvnumber (issue number), txtpages (page numbers), journalname, authors, puburl (link to electronic full text source of the article)

Table: tblpub_list (the Publications List table)

Fields: intpubid, txtpubabname, txtpubname

Table: topics, (the Topics table)

Fields: ID, level1, level2, level3, level4, level5 (these refer to the five dimensions of the database), text, description

Table: topics_link, (the Topics Link table)

Fields: intartid, removed, inttopicid

The database is highly 'relational' in that the Articles table has a field, 'intartid', the Topics table a field, 'ID', and the Topics Link table a field 'intartid', all of which are referenced by other tables. The importance of these relations is best illustrated by understanding the code necessary to accomplish the Search task: Chosen topics are queried by their ID and the resulting level values are pulled into the web program. To find all subtopics associated with the chosen topic, the Topics table is queried to find all topic ID's, which have the same level values up to the last non-zero level of the original chosen topic. Matching articles are then found using the Topics Link table. The 'inttopicid' field is the 'ID' field from the Topics table. The 'intartid' field is the Articles table 'intartid'. Thus all article IDs that have topic IDs of all topic subsets can be found through query. Those matching all the chosen topics or subtopics are displayed.

Data Entry

The data entry process is formalized according to widely used reference-citing procedures. To submit a reference into the database, the researcher simply navigates to the publication entry link of the database homepage and fills the fields listed above with the critical publication identification information. There are fields for title, abstract, uniform resource locator (URL), publication source, year, volume, number, pages, and authors. To identify the publication source (e.g., journal, magazine, conference, etc.) the researcher either selects from a list of previously identified sources under the heading 'journal' or chooses to

identify the name of a new source. To enter a new source into the database, the researcher simply inputs the source name into the 'enter new journal' field and clicks on the corresponding entry button. The new source will then be located among the list of previously entered sources. The researcher would then be required to locate, highlight, and enter the new source into the 'journal' entry field. Figure 1 below depicts the data entry interface.

Figure 1. Screenshot of the data entry interface for the human error and technological interventions database. The top portion of the interface simply contains fields where relevant publication information may be entered. At the bottom, the entry will be mapped into the five dimensions of the database structure via drop-down menus containing the respective taxonomies for each dimension.

One of the preliminary aims of the database is to allow users to make inquiries with stringent parameters in hopes of locating publications that are specific and relevant to the research at hand. This feature is instrumental in providing the end user with the capability of locating error mitigation technologies. The unique aspect of the database is that it allows the researcher to determine the human factors dimensions that are relevant to their research and enter them into the 'topic selection' subcategory. Not all publications will be specific enough to fulfill the requirements of every taxonomic dimension; however, the more spe-

cific the data entry is, the more powerful the database will be. The original database included five taxonomic dimensions with hierarchical taxonomies including 'human', 'environment', 'task', 'error', and 'technologies'. The 'human', 'environment', and 'task' taxonomies make up the three axes that form the basic structure of the database. The initial population of the database showed that many publications could only be classified according to these three taxonomies. For some articles, the 'error' and 'technology' dimensions were either too restrictive for reliable classification of entries, or because most published studies simply did not make sufficient references to human error or particular technological interventions. A very small proportion of the literature reviewed could be classified to all five taxonomies. Another significant finding suggested that the original 'technologies' dimension, based on NASA AvSP, was not sufficiently exhaustive. Many publications were discovered that discussed technologies not included in this system. Therefore, a sixth taxonomic dimension, which mimicked the 'journal' field, was added as an extension of the 'technologies' dimension to support updates to this dynamic domain and to test the functionality of such a feature. The database currently only allows for the 'technologies' field to be updated; however, the other dimensions will be fully editable in future iterations.

To ensure the highest quality of data entry, a 'selected topics' window is available for the researcher to review the relevant topics of intended input. In this window, the researcher will notice a compiled list of relevant topics and corresponding identification codes. If the researcher identifies a mistake, an option to 'reset topics only' or 'reset whole page' is designated by corresponding buttons at the end of the entry page. If the researcher is satisfied with the data entry, the final step in the entry process is to click the 'submit article to the database' button at the end of the page.

Publication Search

Becoming familiar with the data entry features of the database allows for better navigation of the search function. This function is no different from a typical database search page in that it allows the researcher to search by 'title keyword or phrase' or by 'author keyword'. What makes this database unique is that it allows the researcher to enter human factors topics based on the five dimensions within the human error and technological interventions structure. Figure 2 depicts a screenshot of the search interface, with the error dimension expanded for selection.

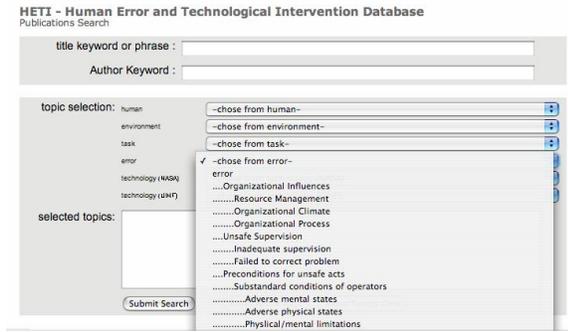


Figure 2. The search interface for the human error and technological interventions database. The database may be searched conventionally by title keyword or author name, but the unique feature of this application is search through any of the five dimensions of the database structure (i.e., human, task, environment, error, or technology). In the above figure, the error menu is expanded.

Testing and Evaluation of the Database

The database was tested by entering a literature review and conducting subsequent searches. The search capability was tested by gradually refining the search criteria. The process of testing the search function of the database after it was populated with a significant amount of data using this method yielded some interesting findings. The overall function of the database is acceptable as it progressively returns fewer articles as more search criteria are added to the search function. For example, searching under the 'human' dimension subheading 'senses' will return more publications than searching under the subheading 'vision,' which is on a lower order in the taxonomical hierarchy. And searches using a single criterion of 'vision' would return more publications than searching under the criteria of 'vision' coupled with 'cockpit' subheading of the environmental dimension. Subsequently, even fewer articles would be returned through a search conducted for 'vision,' 'cockpit,' and a 'synthetic vision system' technology. These findings emphasize a major strength of the database and support the purpose for which it was conceived; however, as mentioned before, the amount of publications in the current database that incorporate error mitigation technologies within their context is relatively small.

A significant problem with the database that was encountered during this phase of the research was that the database was turning up erroneous results when the researcher would attempt to search for publications using the sixth entry field that served as an extension of the 'technologies' dimension. The prob-

lem with a search using this new field is that the coding did not allow for a hierarchical designation. While the other fields have categories with subcategories that are coded according to the levels at which they appear in the hierarchy, this new field coded all new entries with the same level, level 6 in this case, followed by all zeros. This result highlighted the importance of rigorous taxonomy development and verification.

The search output contains a complete citation of the articles as well as listing of all topics (i.e., also those that may not have been part of the search criteria) associated with them. The output appears in the same browser window as the search interface, directly below it, allowing for easy and quick subsequent searches with refined criteria. Figure 3 below depicts the output format.

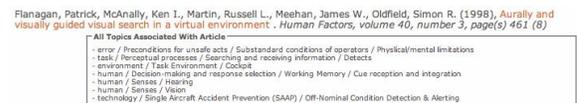


Figure 3. Screenshot of a sample output from database search. The colored title of the article serves as a link to an electronic full text source. Below the citation, all topics associated with this article are displayed.

Summary and Conclusions

Contributions of human error to aviation accidents have traditionally been addressed by different technological 'fixes', aimed either at reducing the occurrence of errors or at mitigating the negative consequences of errors. New technologies and system changes may also introduce new error opportunities or induce different types of errors, however. Thorough understanding of the relationship between error classes and technology 'fixes' is therefore crucial for the evaluation of intervention strategies and effective direction of resources to maximize the benefit to flight safety.

The database described in this paper was created to map intervention technologies onto error categories for their thorough evaluation in light of available research literature. We also sought to create a conceptual framework for this important topic and identify applicable taxonomies for each dimension of this framework. To test this framework, we created a usable prototype database with a web interface. The database, however, can be completely tested only after it has been sufficiently populated. As classification and entry of relevant research literature into the database must be done manually by human factors ex-

perts, realization of the full potential of the database is deferred into the future. The web interface for distributed database management is proposed to address this problem, and it is our hope that researchers involved in aviation technologies development worldwide would partake in continual updating of the database contents and its testing and evaluation.

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