JOURNAL OF AEROSPACE COMPUTING, INFORMATION, AND COMMUNICATION
Vol. 3, April 2006

Analysis of Ease-of-Use and Ease-of-Learning of a Modern Flight Management System

Lance Sherry*
San Jose State University Research Foundation, Moffet Field, CA, 94035

Karl Fennell†
United Airlines, Denver, CO

Michael Feary‡
NASA Ames Research Center, Moffet Field, CA, 94035

Peter Polson§
University of Colorado, Boulder, CO, 80309

The Flight Management System (FMS) has been identified by researchers, airline pilots, and airline instructors as hard to learn and difficult to use. Using the FMS to execute airline mission tasks requires the development and maintenance of a pilot's cognitive skills to interact with the FMS user-interface. This cognition is guided by visual cues (e.g. labels, prompts), user-interface conventions, and memorized action sequences. Pilot actions prompted by visual cues on the user-interface take less time to learn and reduce the likelihood of errors while performing infrequent tasks in revenue-service operations. The analysis described in this paper identified the presence of visual cues to completely guide all pilot actions for twenty five percent (25%) of 102 airline mission tasks performed using a modern FMS. Further, forty-five percent (45%) of the tasks were identified as occurring infrequently and were <u>not</u> completely supported by salient visual cues. The low percentage of tasks supported entirely by visual cues contributes to pilots perceptions about the difficulty in learning and using the FMS. Implications for training the FMS and the design of improved user-interfaces are discussed.

Introduction

ONE of the investments made by airlines is in the development and maintenance of pilot cognitive skills to perform airline mission tasks using the Flight Management System (FMS). Airline mission tasks include: executing Air Traffic Control (ATC) instructions, responding to equipment cautions/warnings, and performing checklist items and airline operating procedures. The user-interface for the FMS is the Multi-function Control and Display Unit (MCDU) illustrated in Fig. 1.

Received 7 September 2005; revision received 6 January 2006; accepted for publication 28 January 2006.

* Senior Research Associate, Human Factors Research & Technology, NASA Ames Research Center, MS: 262-4, Moffet Field, CA 94035.
† Senior Instructor, Boeing 777 Fleet, United Training Center, 7401 Martin Luther King Blvd, Denver, CO, 80207.
‡ Research Psychologist, Human Automation Integration Research, NASA—Ames Research Center. MS: 262-4, Moffet Field, CA, 94035.
§ Professor, Department of Psychology, 2690 Heidelberg Dr. Boulder, CO, 80309.

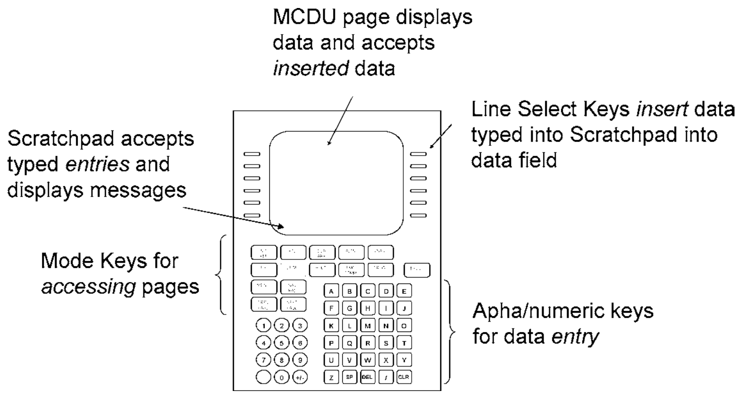

Fig. 1 Multi-function Control Display Unit (MCDU) is the user-interface to the FMS. User accesses pages via Mode Keys, *enters* data into the Scratchpad via the alpha/numeric keys, and *inserts* the entries via the Line Select Keys.

Investigations by researchers of modern airline cockpit operations have identified issues related to the learning and use of functions provided by the FMS. Pilots described the experience of learning to use this automation as "drinking from a fire hose",[1] and only achieve skilled and efficient use of the system after 12 to 18 months of line experience.[2]

Several studies and surveys of pilots have consistently revealed that pilots have difficulty in using the features of the FMS during line operations due to gaps in their knowledge [3–6] and cite the need for more training.[7] Pilots experience using the FMS is summarized by Ladkin[8] as follows:

- "…pilot confusion regarding FMS-presented information is not unusual, even among experienced pilots."
- "Confusion about the FMS presentation, as is true for use of any computer, is often resolved after persistent interaction with it."
- Pilots assume that the "…confusion he was encountering was related to his use of the FMS, and that continued interaction with it would ultimately clarify the situation."

Issues with learning and using the FMS have been attributed to the lack of a detailed conceptual understanding of how traditional pilot tasks are performed by the FMS.[9,10] Other researchers have discussed the awkward layout of the keyboard,[11] the large number of pages and features,[12] the complexity of navigating through the hierarchy of pages, and the inefficiencies in inputting data.[13,14]

Whereas these phenomena contribute to the perceived complexity of the system, the difficulties experienced by pilots in learning and using the FMS are directly related to the cognitive skills that must be learned and used to perform all of the pilot actions required to complete an airline mission task.[15]

This paper describes the results of an analysis of the presence of visual cues on the MCDU to guide the human-computer interaction required to perform a sample of 102 airline mission tasks using the functions of the FMS. The results indicate that pilot interaction with the FMS is not comprehensively supported by visual cues on the user-interface. These results have implications on the way pilots should be trained, and on the way future generations of the automation should be designed and certified.

The next section of this paper provides a simplified model of pilot-automation interaction for performing airline mission tasks using the automation. The following section describes the method of analysis of the human-computer interaction of the airline mission tasks used in this study. This is followed by the results of the analysis. The final section discusses the implications of these results and future work. This paper is a summary of the NASA/TM-2003-212274, *Drinking from the Fire Hose: Why the FMS is Hard to Learn and Difficult to Use*.[16]

Pilot Interaction with the FMS

Pilot-automation interaction can be modeled by a two-way communication between pilot and automation.[12] The pilot communicates intentions to the FMS using Mode Keys (also known as Page Select keys), Line Select Keys, and the Scratchpad on the MCDU user-interface (see Fig. 1). The FMS acknowledges pilot commands and provides feedback of its commanded behavior and the changes in the environment via MCDU pages. There are in excess of 38 pages displayed on the MCDU used in a typical commercial airliner.

Pilots Execute Airline Mission Tasks

The pilot's activities in completing an airline mission (i.e. flight leg) can be broken down into the execution of a series of tasks.[14] Airline mission tasks include air traffic control (ATC) instructions, checklist items, response to automation caution/warning, or standard operating procedures (flows). They are triggered by voice instructions, visual indications both outside and inside the aircraft, visual checklists, response to warning/cautions from the automation, or by memorized airline procedures (flows). This paper focuses on the airline mission tasks that are executed using features of the FMS.

Five Step Process for Pilot-Avionics Interaction

The execution of an airline mission task by a pilot can be modeled as a series of five cognitive stages.[16] The five stage model, known as the RAFIV model, is described below:

(1) **Reformulate** the airline mission task into a definition of the function (or feature) of the FMS that will be used, and the data that must be entered.[17] For example, an ATC clearance "direct to waypoint" can be executed using the DIRECT TO feature of the MCDU LEGS page. The waypoint is the data that must be entered.

Once a decision on how to use the automation has been defined, the pilot must perform a sequence of actions to select the FMS function and transfer the data. These actions have been divided into three steps by.[2]

(2) **Access** the right user-interface by physical actions that must be taken on the user-interface to display the fields for data entry. Accessing pages on an FMS this is accomplished by selecting MCDU mode keys and/or navigating the hierarchy of pages on the MCDU.

(3) **Format and Enter** data. Data must be formatted carefully to be accepted by the MCDU pages. For example, the entry of a lateral route offset on the MCDU is <Side L or R><distance in nm.>. Most formatting takes place while typing entries into the scratchpad.

(4) **Insert** data in the correct location. Line Select keys on the MCDU are used to select items and insert data typed into the scratchpad.

The format and insert stages may be repeated several times for multiple entries. For example to complete the instructions for a Hold may include information about the leg length/time, turn direction, radial, and/or quadrant.

(5) **Verify & Monitor** that the automation: (1) has accepted the pilot entry, (2) is performing the intended task within the envelope of acceptable performance, and (3) the FMS function is satisfying the task objectives. This step involves scan and intensive scrutiny of the Primary Flight Display (PFD), Navigation Display (ND), and MCDU. The monitoring stage occurs for the full period of the task. It should be noted that many inputs to the MCDU have no immediate effect, but may impact the flight several hours after their entry.

Example Pilot-Avionics Interaction

An example of the breakdown of the steps to execute an ATC task: "path offset 20 miles right for weather" is shown below.

(1) *Remember* or *Infer* that the MCDU has a **function** known as OFFSET that can automatically modify the flightplan to offset the path. *Remember* or *Infer* that the data required for this function is side (left or right) and distance (in nm.)

(2) *Remember* or *Infer* that the OFFSET function is on the RTE page (not the LEGS page). *See* that the RTE page **accessed** by pressing a mode key labeled "RTE".

(3) *Remember* or *Infer* the **format** for entry of the data is <side><distance>. *Remember* or *Infer* an acronym for side is "L" or "R". The data is **typed** into the scratchpad.

(4) *See* that the scratchpad data is **inserted** in a field *labeled* OFFSET.

(5) *See* the display of data in the OFFSET field and *See* the *display* of modified flight path on the Navigation Display (ND) to **verify** acceptance of entry.

It should be noted that whereas the stages described above are useful for training and analysis, there is no evidence that novice, intermediate skilled, or expert pilots organize their knowledge in this linear manner.

Pilots Actions are Prompted by Visual Cueing, Inference, or Memorized Actions

Each of the five steps can be thought of as being triggered by a combination of:

(i) *seeing* a visual cue for an action sequence, such as a prompt or label on the automation,[18]

(ii) knowledge-based reasoning or *inference* from user conventions or similarities with other tasks,[19] or

(iii) *remembering* a memorized action sequence.[20]

For the "path offset 20 mile right for weather" task used in the example above, the pilot uses salient visual cues to guide the action sequences for steps, 4, and 5. The pilot must infer the action sequences from user conventions or similar tasks, or recall a memorized action sequence, to perform steps 1, 2, and 3.

Visual Cues Result in Reduced Training Costs and Improved Cockpit Operations

Pilot actions that are guided by visual cues require less time to train to reach competence than those pilot actions that rely on inference or memorized action sequences. This phenomenon has long been established in the analysis of office automation and in analysis of Human-Computer Interaction.[21,22]

Similar results have been found in airline cockpit operations.[23,24] A recent study of cockpit operations of 20 C-130 pilots qualified on a new advanced FMS provides some sense of the role of visual cues.[25] The likelihood of a pilot committing an error in accessing the correct display was 74% when two pilot actions were required and neither was guided by visual cues. The likelihood of a pilot committing an error in accessing the correct display was 13% when a single pilot action was required and was not prompted by a visual cue. In contrast, when the pilot action was visually cued, the likelihood of a pilot error was 6%.

Steps with memorized action sequences require constant use to avoid forgetting. Tasks with memorization actions that occur infrequently (i.e. less than once a month) are subject to forgetting.[18,26] When a pilot is confronted with an infrequent task with a memorization action that is forgotten, the pilot must resort to inferencing using knowledge about user-interface conventions, knowledge about similar tasks, or problem-solving by trial-and-error exploration of the user-interface.[27] This process requires focused attention and cognitive processing that drives up pilot workload resulting in less efficient cockpit operations and a reduced margin of safety.

Method of Analysis

The purpose of this study was to identify the presence of visual cues to prompt pilot action sequences in the conduct of airline mission tasks using the FMS. The degree to which action sequences are not supported by visual cues would explain the perceived difficulties in learning and using the automation experienced by airline pilots.

Analysis

A sample of 102 mission tasks defined in the Honeywell B777 Pilots Guide [28] was analyzed. Each mission task was described using the 5 stage RAFIV model. Each task was classified as Frequent or Infrequent. Each RAFIV step of the task was classified as See based on the existence of salient visual cues to aid in the performance of the step. A step without any visual cue prompting the action sequence was designated as a Remember/Infer step.

Task Selection

The tasks used in the analysis were MCDU tasks defined in the Honeywell B777 Pilots Guide. Since this manual is a "system description," the tasks were culled by parsing the manual section by section and pulling out descriptions that were associated with the pilot performing tasks using the FMS. All of the airborne operations tasks listed in the Pilot's Guide were included. Pre-flight tasks were not included.

Since the tasks were listed in the Pilots Guide, the list of tasks used in this study included only tasks that could be performed by the FMS. Tasks that are not directly supported by the FMS were not considered.

Team

The tasks were classified and analyzed to criteria by the team of authors that included; one flight instructor with 16 years experience at a major U.S. airline, one senior cognitive scientist with over 40 years experience, one twin jet-engine rated pilot with 10 years of experience as a human factors researcher, and one avionics design engineer with 18 years experience designing these systems. All classifications of the tasks were made by complete concurrence of all parties. Differences between individual assessments were few in number and could be attributed to an absence of detailed domain knowledge or initial ambiguity in the classification criteria. The authors believe that a group with similar domain experience would be able to conduct the classification with very similar results.

Criteria for Classification of See or Remember/Infer for each RAFIV Step

Each task was described by the RAFIV steps. A *reformulate* step was classified as a *See* step if the user-interface provided a visual indication that:

(i) the automation feature was labeled and visually salient. That is, an ATP certified pilot without experience using the FMS could use domain knowledge to reason that the function exists in the FMS (under the assumption of shared terminology).

(ii) the task could be performed using a feature of the automation (and not broken down into several sub-tasks for indirect application of several automation features).

(iii) the data (e.g. ATC instruction) could either be entered directly or the user-interface cues any mental computation (e.g. compute reciprocal) required.

A reformulate step that required mental calculation of parameters, knowledge where the function was "hidden" in the automation displays, and/or a deep understanding of automation unique representations classified as *Remember/Infer*.

An *access step* was classified as a *See* step if the input device to access the feature was clearly labeled or prompted. Otherwise the step was classified as a *Remember/Infer* step. For example an appropriately labeled mode key or line-select prompt provided visual cues for a See classification.

A *format step* was classified as a *See* step if the format for data entry was displayed (e.g. labeled field, default values, list of options). If the step required recalling the format from long-term memory or inference from user-interface conventions, then the stage was classified as *Remember/Infer*.

An *insert step* was classified as a *See* step if the location of entry was labeled. Otherwise the step was classified as *Remember/Infer* step.

A *verify and monitor step* was classified as a *See* step if the automation provided feedback that confirmed the progress toward the task goals. The step was classified as a *Remember/Infer* step if the step required mental calculation of parameters, knowledge where the function was "hidden" in the automation displays, and/or a deep understanding of automation unique representations to verify and monitor the task. It should be noted that this study limited analysis of verification and monitoring only to those visual cues displayed on the MCDU and not those on the ND and PFD. For this reason, the verification and monitor results are provided in this report, but there is no discussion of their merits.

Frequency Criteria

Tasks were classified as frequent if they occurred at least once a month in typical revenue service. A typical B777 airline pilot, flying a standard U.S.-Europe schedule, will fly five 3-day trips a month, including 10 flight legs. As a consequence, frequent tasks occur at least once in every ten flight legs (e.g. Direct To). Tasks were classified as infrequent if they occurred once in every ten flights or more (i.e. less than once a month). An example RAFIV analysis for the "path offset" task is illustrated above.

Results of Analysis

A total number of 102 airline mission tasks were found in the airborne section of the Honeywell B777 Pilot's Guide. A complete list of the tasks can be found in Appendix of Sherry et.al.[16]

There are three major findings:

(1) Twenty five percent (25%) of the tasks are completely supported by visual cues for all the steps required to perform the task. Seventy five percent (75%) of the tasks require one or more inferenced or memorized actions.

(2) the steps least supported by visual cues on the user-interface are the Reformulate step (30% of the tasks supported by visual cues) and the Access step (55% of the tasks supported by visual cues).

(3) 40% of the tasks occur frequently enough not to warrant the use of visual cues. Fifteen percent (15%) of the tasks occur infrequently, but are supported by visual cues. Forty five percent (45%) of the tasks occur infrequently and are not supported by visual cues.

Explaining Training Difficulties

Twenty-five percent (25%) of the tasks are completely supported by visual cues that prompt the pilot in all the steps required for completion of the task. The remaining 75% of the tasks include one or more steps that require the pilot to infer the next step from user-interface conventions, from similarities with related tasks, or by remembering memorized action sequences.

The implication of this result is that the development of pilot skills during training can rely completely on visual cues on the device for only 25% of the tasks. For steps in the remaining 75% of the tasks for which no visual cues are present, the tasks must be trained using external information such as user manuals, training guides, or instructor tips. These external sources must include information about the user-conventions, identify groups of similar tasks, and identify the memorized actions where required.

The percentage of tasks supported by visual cues for each RAFIV step is as follows:

- Reformulate step—40% of the all the tasks
- Access step—65% of the all of the tasks
- Format & Enter step—85% of all the tasks
- Insert step—93% of all the tasks
- Verify & Monitor step—98% of all the tasks

The *reformulate* step, involving the mapping between ATC instructions and features of the FMS, is supported by visual cues for 40% of the tasks. For these tasks, the existence of the FMS feature to support the task is reflected in the labels and prompts on the user-interface (e.g. HOLD). The remaining 60% of the tasks require knowledge of the organization of FMS features, remembering the existence of the feature in the hierarchy of MCDU pages, a significant modification of the task into different or smaller sub-tasks, and/or mental computation of a parameter. For example, the feature for climbing direct to a clearance altitude (without leveling off at intermediate flightplan altitude constraints) is available on the VNAV only when certain conditions associated with the Mode Control Panel (MCP) altitude and Cruise Flightlevel are satisfied.

This result is biased on the low side as this study considered only tasks that can be performed directly by the FMS. Consideration of all the airline mission tasks would include a significant number of tasks that must be reformulated into sub-tasks. For example, the BASI report[1] found that 42% of the pilots indicated that they are required to enter "workarounds" (intentionally incorrect or fictitious data) to ensure that the system did what they wanted it to do. This problem occurred more frequently when pilots were trying to comply with "difficult air traffic control instructions and to compensate for inadequacies during the descent/approach phases of flight".

Sixty five percent (65%) of all tasks are supported by visual cues that prompt the pilot on the action sequence required to *access* the correct MCDU page. This is a consequence of the limit of using 11 mode keys to access features. There are two main classes of Mode Keys (also known as Page Select Keys), those that access functions, and those that access underlying representations that can be manipulated. The PROG, HOLD, DEP/ARR, and ALTN mode keys provide access to functions for performing these tasks. The RTE and LEGS Mode Keys provided access to representations of the flightplan that can be manipulated in several different ways to manipulate the representation.

Access steps classified as See steps are supported by Mode keys with labels that have strong semantic associations with language of the task. Mode keys labeled with representations of the flightplan generally were classified as Infer/Remember (unless the ATC instruction included the phrase akin to "route" or "leg"). For example, the fields that accept the entries for an "offset to the lateral path" are located on the RTE page. The authors observed pilots in training and in revenue service access the RTE page only after first accessing the LEGS page and not being able to visually locate the OFFSET label.

The format & enter step is well supported by salient visual cues. Format and entry of 85% of the tasks are supported by salient visual cues on the MCDU pages that display the desired format, range of entry, and units. The tasks that do not provide visual cues, require the pilot to infer or remember action sequences in support of entry of data whose format is not annunciated on the display. For example, programmed step climb points are entered with format "/<flightlevel>S." The absence of the slash or S will result in failure to complete the task. Most of the tasks classified as Infer/Remember for the format & enter stage involved multi-parameter entries in which order, acronyms, and partitioning (e.g. "/") were required.

Issues associated with format & entry are compounded by ambiguous feedback from the automation when there is a format error (e.g. INAVLID ENTRY or FORMAT ERROR). Pilots in the BASI report specifically cited these scratchpad messages as a source of confusion and suggested that they provide better feedback "to lead the pilot to the source of the problem".[1]

The insert step is well supported by visual cues (92% of the tasks). Problems were the result of the absence of labels. For example, the location for insertion of the Direct To waypoint is not labeled and requires several repetitions in initial FMS training to memorize the location of the insertion at the top of the list of waypoints on the LEGS page. The absence of a label also can cause problems in revenue service when pilots try to insert the Direct To waypoint at the top of the page without first paging back to the first page (1/n) of the LEGS.

The FMS exhibited a very robust design for the Verification and Monitor steps (98% of the tasks). The small number of tasks that were classified as Infer/Remember required interpretation of a feedback message. For example, if an abeam point cannot be computed on the current flightplan, the only feedback to the operator is the cryptic INVALID ENTRY message. As discussed in the methods section above, the Verification and Monitor step was limited to an analysis of the verification of acceptance of the pilot entries on the MCDU page and did not include feedback from the PFD and ND.

For each of the RAFIV steps, training efficiency is compromised by the absence of visual cues on the user-interface. The training program is obliged to provide the pilots with supporting documentation or instructions that develop knowledge that allows the pilot to infer or remember the appropriate action sequence.

Explaining Operational Difficulties

Forty percent (40%) of the tasks were classified as frequent (occurring at least once in a month of revenue service operations). The absence of visual cues does not affect pilot performance for these tasks due to the frequent repetition of actions.

Sixty percent (60%) of the all the tasks were classified as infrequent. Twenty five percent (25%) of the infrequent tasks are supported by visual cues for all of the steps. Seventy five percent (75%) of the infrequent tasks are not supported by visual cues for one or more their steps.

Without proficiency training there is a high probability that these skills, once trained will erode.[15] Pilots flying-the-line are likely to experience difficulty in inferring or remembering how to perform a task that they have seen before but not used in the past year. This phenomenon can be found in several accident reports such as the Cali accident[8] and the NTSB report on pitch oscillations.[29] These tasks must be retrained on a periodic basis to maintain proficiency.

Conclusions

The over-reliance on inference of user-interface conventions, inference of steps for similar tasks, or memorized action sequences to perform airline mission tasks provides an explanation of how the design of the FMS user-interface contributes to pilot perceptions about the relative difficulty in learning and using the system. These results have implications for training and for line-operations.

Pilot Training of Existing Equipment

The results of this study emphasize the need to consider the cognitive aspects of training the FMS during the design of the MCDU pages. Specifically, the absence of visual cues for all the steps in a task extends the number of repetitions required during training for each pilot to reach proficiency. For tasks that are repeated frequently during training (e.g. Direct To), this is not a problem.

Steps in tasks that are not supported by salient visual cues and not performed frequently during training or in revenue service require additional training material. The additional training material should have the following three properties: First, the pilots should be provided with a complete description of all of the steps required to execute all the airline mission tasks. This description should include a definition of the task and a description of the triggering event for the task (e.g. ATC instruction, check list item). This information is critical for the contextualization of the task for the pilot and is now standard in airline training programs qualified under the FAA's Advanced Qualification Program (AQP).[30]

In addition to a description of the task, the training material should also provide a description of the FMS function used to perform the task. The mapping between task and function is the most critical step in developing a robust skill as it is the starting point of the procedure. This mapping is also largely not supported by the FMS user-interface as the majority of the functions are "hidden" behind over-generalized or unrelated Mode key labels. Finally, a description of the access, format, insert and verify steps must also be included.

Second, the RAFIV steps provide a useful framework for organizing the sequence of cognitive and physical actions for each task. As is the case for most systems, the FMS exhibits some consistencies in cognitive and physical actions across tasks. These consistencies provide opportunities to generalize the human-computer interaction skills and stream-line training. For example, tasks can be grouped into task families that share the same FMS function. Likewise there are general rules for accessing MCDU pages, formatting scratchpad entries, and inserting data, which are shared between tasks. By explicitly training this information (and the exceptions), pilots will be given general problem solving skills that will allow them to exhibit robust performance and stream-line learning of new skills.

Third, as shown by this study there are a large number of steps that must be inferred or memorized to become a skillful user of the automation. The training material must reflect this fact by identifying the infer/remember steps explicitly. For tasks that rely on visual cues to prompt action sequences, the explicit descriptions must include information on where to look and how to recognize the visual cues. For tasks that rely on inference or memorized action sequences, well designed training must support learning the inference or memorization steps with appropriate mnemonics and appropriate drill and practice.

Pilot Proficiency In Using Existing Equipment

Pilot proficiency during line-operations for infrequent tasks that rely on inference or memorized action sequences can only be maintained through practice. This could be accomplished using the training material described above and tested (or quizzed) periodically. One proposal is to provide pilots with a device (e.g. laptop FMS simulation, or additional MCDU pages) that allows pilots to practice infrequently used skills during long range cruise operations or layovers.

Design and Evaluation of New Cockpit Equipment

New cockpit systems should be designed with user-interfaces that maximize the use of visual cues, and minimize the need for inference or memorized action sequences. For frequent tasks, this will minimize training time. For infrequent tasks this will minimize training time and improve performance during line-operations.

Sherry & Feary[31] have developed a Task Design Document (TDD) that can be made part of the approved certification process for the development of avionics equipment. The purpose of the TDD is to document the design of the pilot-avionics interaction required to perform all airline mission tasks. In this way the pilot-avionics interaction is not an emergent property of design process, but a deliberate design decision that takes into consideration the effect of the user-interface on training and use.

To provide the basis for a design for efficient training and cockpit operations, the TDD must embody: (i) a definition of the tasks, (ii) the mapping between tasks and intended functions of the avionics equipment, (iii) the sequence of steps used by the pilot to interact with the avionics to perform each task, and (iv) the source (see, infer or remember) for each step.

Airline mission tasks that are complex to execute and mission tasks that require excessive inferencing or memorization of action sequences become apparent in this specification. Re-design of the function or the user-interface may be required. Alternatively, tasks that require inferencing and memorization of action sequences may require a "waiver" from the Program Manager before the TDD Review can be signed off.

Designing Graphical User-interfaces for the Cockpit

Several vendors of avionics equipment have responded to the demand for improved cockpit operations by implementing graphical user-interfaces. Graphical user-interfaces in the cockpit do not inherently address the issues of training and use described above, although several of the features generally associated with graphical user-interfaces do invoke the See (not Infer/Remember) paradigm. For example, pull down lists provide a See mechanism for Format and Insert steps. Likewise, menu structures provide See mechanisms for the Reformulate and Access steps.

Graphical user-interfaces that allow users to manipulate objects (e.g. waypoints) on visual representations of the environment (e.g. aero charts on the Navigation Display) are particularly prone to issues with the reformulate and access step. In several examples that we have reviewed, there are no salient cues as to what functions are available, or how to access these functions. These designs did score exceptionally well on format, enter, insert, and verify steps.

It should be noted that the success of any user interface for the cockpit, graphical or otherwise, lies in the abilities of the designers to understand the airline mission tasks and provide appropriate functions to support these tasks.[14] The design of See (not Infer or Remember) for the Access, Format and Insert steps cannot overcome a mismatch between task and function in the Reformulate step.[32]

Acknowledgments

Special thanks for several technical suggestions to: three anonymous reviewers; Immanuel Barshi, Everett Palmer, Mike Matessa (NASA-ARC); Randall Mumaw, Dan Boorman, (Boeing); Jack Rubino (United Airlines); Steve Quarry, Phil Scandura (Honeywell). Also thank you to Everett Palmer and Rose Ashford (NASA), Kevin Jordan (SJSU), and John Kilroy (Honeywell) for their support. This work was supported by the NASA Aviation Operations Systems Program contract GS09T01BHM0386 order ID 9T1N001MH to Honeywell International CAGR (TPC: Michael Feary) and the SJSU Research Foundation Grant in Human Factors. This paper is a summary of the NASA/TM-2003-212274, *Drinking from the Fire Hose: Why the FMS is Hard to Learn and Difficult to Use* by the same authors.

References

[1]BASI, "Advanced Technology Safety Survey Report." *Flight Safety Digest Special Issue.* Flight Safety Foundation, Alexandria, Virginia. June–Aug 1999, pages 137–216.

[2]Polson, P., Irving, S., and Irving, J., Applications of Formal methods of Human Computer Interaction to Training and Use of the Control And Display Unit. Tech Report 94-08, University of Colorado, 1994.

[3]Mumaw, R., Sarter, N., Wickens, C., Kimball, S., Nikoloic, M., Marsh, R., Xu, W., and Xu, X., *Analysis of pilot's monitoring and performance on highly automated flight decks*. NASA Ames Contract NAS2-99074 Final Report, 2000.

[4]Air Transport Association, *Potential Knowledge, Policy, or Training Gaps Regarding FMS Generation Aircraft.* Automation Sub-committee, Human factors Committee, Air Transport Association, Washington, D.C., 1999.

[5]Federal Aviation Administration, *The interface between flightcrews and the modern flight deck system*. FAA Human Factors Team, Federal Aviation Administration, Washington, D.C., 1996.

[6]Feary, M., McCrobie, D., Alkin, M., Sherry, L., Polson, P., and Plamer, E., *Aiding Vertical Guidance Understanding*. NASA/TM 1998-112217, 1998.

[7]Air Transport Association, *Towards an Operational Philosophy and Model Training Program for FMC Generation Aircraft*. Automation Sub-committee, Human factors Committee, Air Transport Association, Washington, D.C., 1999a.

[8]Ladkin, P., AA965 Cali Accident Report, Near Buga, Colombia, Dec 20, 1995. Peter Ladkin Universit" at Bielefeld, Germany (page 44), 1996.

[9]Sarter N., and Woods, D., *Pilot interaction with cockpit automation I: Operational experiences with the flight management system*. International Journal of Aviation Psychology, 2(4), 1992, 303–321.

[10]Vakil, S. S., Hansman, R. J., and Midkiff, A. H., "Impact of vertical situation information on mode awareness in advanced autoflight systems," *Proceedings of the AIAA/IEEE Digital Avionics Systems Conference*, Cambridge, MA, 1995.

[11]Sarter N., and Woods, D., "Pilot interaction with cockpit automation II: An experimental study of pilot's model and awareness of flight management systems," *International Journal of Aviation Psychology*. 4, 1994, 1–28.

[12]Billings, C. E., *Aviation automation: The search for a human-centered approach*. Mahwah, N.J.: Lawrence Erlbaum, 1997.

[13]Abbott, T, *A Comparison of Two Control Display Unit Concepts on Flight Management System Training*, NASA Technical Memorandum 4744, 1997.

[14]Riley, V., "Cockpit control language: A pilot centered avionics interface," *Proceedings of the HCI-Aero International Conference on Human Computer-Interaction in Aeronautics*. Montreal, Canada.

[15]Rasmussen, J., *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*. Amsterdam: North Holland, 1986.

[16]Sherry, L., Feary, M., Polson, P. and Fennell, K., *Drinking from the Firehose: Why the FMS is Hard to Learn and Difficult to Use*. NASA/TM-2003-212274, 2003.

[17]Palmer, E., Hutchins, E., Ritter, R. D. and Van Cleemput, I., *Altitude Deviations: Breakdowns of an Error Tolerant System*. NASA/TM DOT/FAA/RD-92/7, 1992.

[18]Larkin, J. H., and Simon, H. A., Why a diagram is (sometimes) worth 10,000 words. *Cognitive Science*, 11, 1987, 65–100.

[19]Shneiderman, B., The future of interactive systems and the emergence of direct manipulation. *Behavior and Information Technology*, 1, 1982, 237–256.

[20]Howes, A., "Recognition-based problem solving," *Proceedings of the 15th Annual Meeting of the Cognitive Science Society*. Boulder, Colorado. Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1993.

[21]Boy, G. A., *Cognitive Function Analysis*. Greenwich, CT: Ablex Publishing Corporation, 1998.

[22]Wickens, C. D., and Hollands, J. G., Engineering Psychology and Human Performance. NY, NY: Prentice-Hall, 1999.

[23]Javaux, D., "Explaining Sarter & Woods Classical Results: The Cognitive Complexity of Pilot-Autopilot Interaction on the Boeing 737-EFIS," In N. Leveson and C. Johnson (Eds), *Proceedings of the Second Workshop on Human Error, Safety, and Software Design*. Seattle, WA: University of Washington, 1997.

[24]Martensson, L., and Singer, G., Warning Systems in Commercial Aircraft ndash an Analysis of Existing Systems. Royal Institute of Technology, Dept. of Industrial Economics and Management, TRITA-IEO-1998.

[25]Fennell, K., Sherry, L., Roberts, R., and Feary, M., "Difficult Access: The Impact of Recall Steps on Flight Management System Errors." *International Journal of Aviation Psychology*. Vol. 16, No. 2. Lawrence Erlbaum & Associates: NY. NY.

[26]Farr, M. J., *The long-term retention of knowledge and skills: A cognitive and instructional perspective*. New York: Springer-Verlag, 1987.

[27]Polson, P., and Smith, N. "The cockpit cognitive walkthrough," *Proceedings of the Tenth Symposium on Aviation Psychology*. (pp. 427–432) Columbus OH: Ohio State University, 1999.

[28]Honeywell, Boeing 777 Flight Management System Pilot's Guide. Honeywell Publication # C28-3641-22-00. Honeywell International. Air Transport Systems, Product Support Distribution. PO Box 21111, Phoenix, Arizona, 85036-1111, 1995.

[29]Sherry, L., Feary, M., Polson, P., and Palmer, E., "Autopilot tutor: Building and maintaining autopilot skills," *Proceedings of the HCI-Aero 2000*, Toulouse, France, 2000.

[30]Longridge, T. M, Overview of the Advanced Qualification Program (research issues of interest to the FAA for improving the program). Human Factors and Ergonomics Society, Annual Meeting, 41st, Albuquerque, New Mexico; 22–26 Sept. 1997. pp. 898–901.

[31]Sherry, L., and Feary, M., "Task Design and Verification Testing for Certification of Avionics Equipment," *Proceedings of the IEEE Digital Avionics Systems Conference*, Salt Lake City, Utah, 2004.

[32]Norman, D. A., *The Design of Everyday Things*. Doubleday, New York: N.Y., 1988.