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Toward a Categorization of Factors related to Procedure Following and Situation Awareness

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ABSTRACT

Procedures are used as prescribed action lists to help human operators remember and follow mandatory steps that guarantee safety, workload and performance criteria. This paper presents a categorization of situation awareness factors and suggestions for improving the design of both the procedures and the user-interface in new generation fligh-decks. These categories were constructed from the result of a previous study (de Brito, 1998). should improve concurrent human-centered design of procedures and interface, to contextualize procedures training, to operationalize electronic procedures, and to integrate the revision process. The repercussions on the life cycle of a safety-critical system include concurrent design of procedures and interface, contextualized procedures training, operationalized electronic procedures, and integrated revision process.

Keywords

Empirical findings, categorization, experience feedback, procedure following, situation awareness, software assistants, safety critical systems.

INTRODUCTION

The control of highly automated safety-critical systems is a major issue in industry today. Interfaces between human operators (users) and the complex dynamic systems they control are much deeper than before. These systems include complex software that either amplify users' inputs or interpret system outputs. The increasing complexity of such systems has led to reinforcing procedural prescriptions (Guyot et al., 1996). Procedure following is examined in detail from a series of field studies (Degani & Wiener, 1990; Dixon, 1987; Fisher, 1992; Veyrac, 1998). This paper presents an operational synthesis of the results of an empirical study of the procedure-following paradigm [8]. Categories of situation awareness factors are deduced in the perspective of improving human-centered design of related user interfaces. This categorization process highlights the procedure-interface duality in terms of expertise and complexity, situation patterns and focus of attention, indexing, real-time information retrieval and situation categorization, interruption handling, and procedure consistency issues. Repercussions on the life cycle of a safety-critical system are provided.

THE PROCEDURE-FOLLOWING PARADIGM

In aviation, procedures have been developed to help the crew stay "ahead" of the aircraft, i.e., procedures enable the crew to anticipate actions and avoid forgetting to do what has to be done. Procedures are currently available on paper or in electronic form. They are usually a pre-programmed sequence of elementary tasks that a user should perform to accomplish a specific goal in a specific environment. They are presented in the form of simple lists of actions or more sophisticated algorithms that users should perform (Figure 1.) In aeronautics, a procedure is made to be executed sequentially.

STABILIZER JAM
- MAN PITCH TRIM..... CHECK
■ **IF MAN TRIM AVAIL :**
- TRIM FOR NEUTRAL ELEV
● **if normal law lost :**
F/CTL ALTN LAW (PROT LOST) See previous page
■ **IF MAN TRIM NOT AVAIL and normal law active :**
- LDG CONF 3..... SELECT
- GPWS LDG FLAP 3 ..... ON
- etc.

Figure 1. Example of a procedure that enables the pilot to identify if the manual trim is available or not; actions are different in each situation.

Two major types of procedures should be distinguished: normal procedures that are followed in *normal* situations mainly to anticipate future events or validate executed actions (usually called checklists); and *abnormal* and *emergency* procedures that are used in failure management situations (usually called dolists.) Checklists and dolists are (or should be) designed to structure operations, prevent human errors and enhance situation awareness.

INVESTIGATION RATIONALE AND METHODOLOGY

Pilots often attempt to make sense of a safety-critical situation instead of routinely using checklists or dolists. They constantly make cognitive trade-offs to optimize human factors such as workload and performance,

according to constraints such as safety and passenger comfort. We have tried to prove this claim by using four different methods in real-world aviation environments:

- A task analysis to identify possible discrepancies in the use of checklists and dolists. This preliminary work has determined qualitative and quantitative factors and assumptions that were explored by using the following methods.
- A questionnaire completed by airline pilots. Ten airlines from North America and Europe were consulted, 600 questionnaires of 35 questions were sent and 207 returned fully-completed, 8045 answers and 4554 additional free-text comments were processed. An exhaustive statistical analysis was performed to elicit emerging human factors.
- Observation protocols in full-flight simulators at Airbus Training in Toulouse: 35 crews (70 pilots) were observed for 140 hours of simulation. This investigation provided real activities of airline pilots involved in procedure following.
- Three knowledge elicitation workshops involving 30 airline pilots using the Group Elicitation Method (Boy, 1996). This method provided consensus and divergent opinions that were useful to improve our understanding of some results from the other methods.

Results from these four approaches were compared and further analyzed in order to make categories of factors. This paper focuses on situation awareness factors.

SITUATION AWARENESS FACTORS AND SUGGESTIONS TO IMPROVE HUMAN-CENTERED DESIGN

Users' situation awareness is difficult to observe. However, inappropriate or incorrect situation awareness can be interpreted in terms of situation awareness factors from observed differences between prescribed tasks and effective tasks actually performed by users. The categorization process was carried out using the cognitive function analysis methodology and guided by the four dimensions of the AUTO pyramid (Boy, 1998):

- **A**rtifact being studied, e.g., the cockpit that includes artificial agents (commonly called automation);
- **U**ser, e.g., the pilot;
- **T**ask to be performed, e.g., flying;
- **O**rganization/environment, e.g., the other pilot, air traffic control, crew, and other external events.

In the following classification, situation-awareness factors are labelled with a ✷ sign, and the suggestions for improved human-centered design are labelled with a ⇒ sign.

Artifact-related factors

In the following analysis, the artifact denotes both the user interface, i.e., the cockpit, and the procedures whether they are paper-based or in electronic form. Artifact-related situation-awareness factors can be classified according to three classes of work support:

✷ *Static aspects of the artifact:*
- ⇒ consistency: intrinsic (unambiguous and correct text, non-confusing logic, no missing steps) and extrinsic consistency (good match between description and equipment as well as within a family of airplanes) should be checked;
- ⇒ support size: an appropriate (sheet and screen) size should be provided to display a global view of what the pilot is required to do in the current situation;
- ⇒ unambiguous labeling; no convention conflict; appropriate distance and position; system ergonomics (unambiguous information, adequate contrast, parallax, right size letters and symbols); affordances [19] (appearance and suggestivity, action commonality, novelty of the artifact.)

✷ *Dynamic aspects of the artifact:*
- ⇒ interruptions: software assistants (including checklists and dolists) should not interrupt ongoing user activities;
- ⇒ context-sensitive information display: pilots would like to have a hierarchical presentation of the systems that are connected to inoperative systems after failure according to the right flight phase;
- ⇒ access facilitation: the pilot should be able to access the relevant procedure at any appropriate time; there should be a clear relation between control device actions and signals or cues; signals or cues should be appropriate, non-conflicting and visible; appropriate level of system complexity should be timely presented.

User-related factors

Users have temporary causes of inappropriate or incorrect situation awareness such as: attention failure; memory failure; operational mode misjudged; physiological needs; fatigue; recent failures; time pressure; high workload; or the wrong feeling of knowing what to do. These causes can be used for the following classification according to five high level cognitive functions as situation-awareness factors:

✷ *Discrimination problem:*

Factors such as stereotype fixation, familiar shortcut, stereotype take-over or familiar pattern not recognized may lead to unwanted consequences such as reading the wrong indicator or value, failure to notice a signal or an alarm, or incorrect and incomplete recognition of value.

- ⇒ attention allocation should be identified early enough during the design process.

✷ *Input information acquisition problem:*

Factors such as information not received, misinterpretation or assumption may lead to an identification failure such as incorrect assumptions, incorrect or incomplete recognition of state, or ambiguous information.

⇒ alternatives should be clearly presented to support pilot's information acquisition.

- *Recall problem:*
  Factors such as wrong test, wrong alternatives or other slip of memory may lead to a diagnosis failure such as misinterpreted or confused symptoms, or unfamiliar situation.
  ⇒ prefer recognition instead of recall and display a minimal number of alternatives to the user (one is best!)
- *Decision making:*
  Decision is often anticipated or postponed: some pilots either anticipate future workload periods and start checklists in advance, or postpone the execution of a checklist when they are overloaded (92% of the interviewed pilots said that they are much more interested in the immediate safety of the flight than on starting any dolist.) Factors such as lack of training, long interval since learning, over-generalization, or inadequate knowledge may lead to decision paralysis (shock, fear, ...), wrong decision rule selection, deduction failure, condition or side-effect not considered, or induction failure.
  ⇒ improve training, present appropriate alternatives whenever possible.
- *Understanding:*
  ⇒ before action: pilots need to understand the nature of the situation before acting; checklists and dolists should be designed to support understanding of the nature of failures; procedures should provide rationale of prescribed actions and their consequences; training enables pilots to better acquire situation patterns in order to anticipate the right actions in the right situations;
  ⇒ during action: pilots should control the situation at all times, i.e., they should be informed of the effects of their actions at all times and the repercussions of prescribed actions for example;
  ⇒ after action: pilots should have the status of what has been performed, i.e., a synthetic account of the application of the procedure, and the system state evolution for the rest of the flight.
- *Actual action:*
  ⇒ prefer error tolerance when risk is minimal;
  ⇒ prefer error resistance when risk is high.

Task-related factors

Task-related causes of inappropriate or incorrect situation awareness can be classified with respect to their effects as situation-awareness factors (this is related to what was described for user-related causes since task effects result from user activity):

- *incorrectly timed action*: delay, omission or premature action;
- *action out of sequence*: jump forward (omission as a special case), jump backward, repetition or reversal;
- *incorrect action*: branching, capture, intrusion or side tracking;
- *incorrect duration*: too long/short duration.

These effects can be interpreted in terms of the following causes of inappropriate or incorrect situation awareness: incorrect choice of alternative; no choice made; slip. Suggestions for improved human-centered design of the task are:

⇒ organize checklists, dolists, status, secondary failures, limitations and permanent data by contexts of use;
⇒ anticipate repercussions of the execution of checklists and dolists at design time;
⇒ reduce the sharing of checklist action items among crew members: in current checklists, action items are overly shared by crew members and this may cause errors;
⇒ clearly indicate executed checklist and dolist items on the screen (in green color and using a prompt for example.)

Organizational-environment-related factors

A simple classification of organizational-environment-related situation-awareness factors can be developed according to the available work support from a multi-agent perspective:

- *Communication:*
  Factors such as interruptions (68% of the interviewed pilots said that they abandoned the execution of a checklist after an interruption of the air traffic control) or noise may lead to message misinterpretation or distraction.
  ⇒ train users to systematic information cross-checking;
  ⇒ display the current checklist on a dedicated screen showing already-performed actions using an appropriate color and alerting the user of actions remaining to be performed.
- *Cooperation and coordination:*
  ⇒ role assignment: each crew member should clearly understand what his or her role is, and the repercussions of his or her actions;
  ⇒ redundancy handling: important information should be cross-checked, delegation is not clearly understood, there are conflicting priorities, or a management problem;
  ⇒ checklists as a mediating tool: most pilots say that they wait for the other pilot to be available before starting a checklist for instance.
- *Conflicting activities and priorities among actions and/or agents:*
  ⇒ action items sharing should be better defined according to situations and pilots roles.

THE PROCEDURE-INTERFACE DUALITY

The more an interface is transparent (i.e., it enables the user to understand what should or can be done at all

times), the less the user needs to follow procedures. Conversely, the more an interface is obscure or opaque, the more the user needs assistance, and in particular procedures. This issue was already described as the procedure-interface duality (Boy, 1998).

Expertise and complexity

The types of issues that we raise in this paper are typical of interfaces for technical experts. Most aircraft pilots need to be trained for a long period of time before becoming operational, i.e., able to fly using a cockpit interface. They are technical experts in the sense that they know about thrust, lift, laws of physics, and other aviation-relevant parameters. They know how to handle aviation complexity, in particular their expert situation awareness requires deep technical knowledge about the system they control. In some situations however, when these users do not technically understand how to use the system, they use common sense and think by analogy. In all cases, expert users want to understand the situation, e.g., what they should and can do, what they have done effectively, and what will happen consequently to their actions.

When a system is intrinsically complex, two usability strategies are possible: hide complexity by providing a user-friendly interface, or present schematic views of the complexity. While regular users usually like the former type of interface, the latter type is for technically knowledgeable experts only. The addition of software assistants to the interface tends to hide complexity and remove expertise requirements, even if it often introduces new kinds of complexity. This human-centered automation problem raises the issue of choosing between creating a new job (usually by delegating old jobs to software assistants), training users to cope with complexity, or redesigning using existing experience feedback. Since current solutions promote the development of software assistants, they need to be accountable at any time, and provide summary information about what they have done, are doing and will do next. This does not remove the need for training users to cope with the complexity resulting from introducing software assistants.

Situation patterns and focus of attention

Flying an airplane requires attention in supervising systems and software assistants at all times. While the number of parameters to be controlled is finite, the number of possible situations is quite large. Pilots need to acquire, refine and appropriately use a large number of situation patterns from both training and real flight situations. Pilots build categories of situations, organize them into contextual hierarchies. In general, crews are good at figuring out physical situations and knowing when they are overloaded. They are not good at understanding the behavior of a software assistant. In highly-automated safety-critical systems, this issue is crucial. For this reason, situational rules are incrementally constructed from the appropriation of provided procedures and their refinement into more sophisticated pairs of situation patterns and more efficient actions. Situation patterns may be seen as problem statements that, if they are triggered, lead to the execution of appropriate actions.

The focus of attention is commonly characterized by an appropriate set of situation patterns in the short term memory. Any interface artifact that would activate this set (abduction) would be extremely useful to pilots. The main problem with the use of currently-designed procedures is that their explicit situation patterns are extremely simple and context-free. The result is that the analytical part of a procedure is usually either too complex because procedures designers have analyzed and included all the necessary conditions, or too simple because context was not available at design time.

Indexing, real-time information retrieval and situation categorization

Procedures can be indexed by keywords, by operational phases, by type of abnormal conditions, or by systems and sub-systems they document. In all cases, interviewed pilots insisted on the need for cross-references, or in the diagnosis case information about interconnected faulty systems. In situations of stress, it is difficult to focus on tables of contents for example. Today, operational information is stored in several paper documents. The result is that the user jumps from one manual to another to obtain explanations on a subject that is not immediately self-explanatory, or to obtain precision on how a system works when the description of the appropriate interaction is in another document. The paper-based linear organization of the information is generally inappropriate to its non-linear use required by rapidly changing situations in practice. Access to documentation in context is a difficult research problem. It requires an incremental categorization of situations based on frequency of occurrence, relevance, importance in terms of associated risks and organizational requirements. Context representation remains a key issue not only to enable better indexing mechanisms and subsequently a better access to current procedures, but also to improve human-centered design of future systems.

Interruption handling

Current paper-based operational procedures seldom anticipate interruptions. The present study showed that when pilots are interrupted in the execution of a procedure, they do not often terminate it. In addition, interruptions generate omissions. It is not possible to anticipate all potential interruptions, and even store them in paper-based manuals; this would be too heavy and furthermore incomplete. However, the development of a typology of interruptions is likely to improve both design and training. Electronic procedures enable the system to monitor user's actions and inform the user when a procedure is not completed. When interruptions are detectable by the system, the system could handle them and priorities could be assigned to these interruptions, e.g.,

the priority of an interruption resulting from a failure is often higher than the priority of an air traffic control interruption. Some interruptions could be delayed when their priority is low.

Procedures consistency issues

Consistency is twofold: intrinsic, i.e., internal to procedures themselves, and extrinsic, i.e., between procedures and systems that are documented, as well as within a family of similar systems. In both cases, consistency may be improved: lexically (consistency of terms and symbols); syntactically (the way terms and symbols are organized); semantically (the meaning of terms and symbols); and pragmatic (various ways the same information is used and understood.) These improvements are currently supported by the COHERE (Common Object-oriented Hypertext Editing and Revision Environment) project (Novick & Juillet, 1997), that consists of the development of an interface that facilitates the creation and management of consistent technical documentation. This is specifically important to guarantee the integrity of the manuals of safety-critical systems. This system is being applied to improve the development and the revisions of aircraft operating manuals.

Contextualized procedures training

Procedures training should be performed in context. For instance, in Line-Oriented Flight Training (LOFT) crews are asked to fly a full-mission simulation that is videotaped from start to finish (Foushee & Helmreich, 1988). LOFT sessions tend to enhance contextualization of procedures. Cockpit Resource Management (CRM) is also a training technique that addresses situational, sociopsychological, and other factors that influence aircrew performance. CRM enhances crew cooperation and coordination through the use of procedures. Pilots need to understand why they are required to execute a prescribed action. For that matter, action rationale should be taught and easily available when necessary at any time. Since situation understanding is key, the following issues are very important during training: be analytic when there is time available, i.e., this is a good time to learn the rationale of procedures; be situational, i.e., use already made situation patterns that leads to immediate actions under high time pressure.

REPERCUSSIONS ON THE LIFE CYCLE OF A SAFETY-CRITICAL SYSTEM

Concurrent design of procedures and interface

Operational procedures are a mandatory complement to the interface for users to perform their assigned tasks. They describe how, when and why to perform the task. They provide a semi-rigid framework that guides human-machine interactions. However, once the interface and its functionality are designed, operational procedures are almost fully determined. Current practice shows that they are designed when the system they document is fully developed. This is too late. In too many cases, operational procedures compensate for some design flaws. Thus, procedures and interfaces should be concurrently designed from the beginning of the design process.

The concurrent design of both the interface and procedures takes into account at the same time both user's and system's logic. Active Design Documents (ADD) are developed as mediating tools to support this human-centered design approach. An ADD includes three components: interaction descriptions that specify the task to be performed and then the procedures; interface objects that provide an interaction medium for testing various affordances and functionality; and an evaluation space where usability and utility test results are stored for traceability purposes. This participatory design tool enables design teams to anticipate factors such as interruptions, omissions, procedures completeness and rationale, adequacy between procedures and interface, simplicity, efficiency and workload.

Operationalized electronic procedures

We anticipate that the next generation of aircraft should have fully integrated electronic checklists and dolists that will tend to decrease workload, simplify the execution of the prescribed task, detect omissions, provide the aircraft state integrated within the procedures at any time (this enhances contextualization of procedures), and increase pilots' reaction speed. Procedures should be more operational. They should enable pilots to group items easily, to execute procedures non-sequentially, and to annotate when required. Pilots should have a global view of the procedures since a current solution is to organize them by level of importance with respect to context. Level 1 should correspond to the actions to execute to insure immediate safety. It should include dolists used as confirmations more than prescriptions. Level 2 should present the rationale of Level 1 actions. Level 3 should present deeper descriptions available for training and in low workload situations (Blomberg, Boy & Speyer, 2000).

Integrated revision process

The revision problem has not found a satisfactory solution yet. Revisions management for an operational documentation of safety-critical systems involves both people and documents. Pilots want to be sure that the information they have in operational documents is actually related to their aircraft. Indeed, pilots may move from one aircraft to another. Operational documentation may also change at the same time. In particular, they need to identify obsolete pages and test documentation consistency after several revisions. In addition, there are delays between the time a modification is made and the time the pilots receive appropriate revised pages. These delays need to be reduced. The use of computer networks such as the Web or specific intranets, is likely to provide appropriate solutions.

DISCUSSION AND CONCLUSION

Factors related to procedure following and situation awareness bring the issue of procedures-interface duality. Compromises between procedures and user-interface should be found early enough during the design process. This should avoid the late production of complex procedures that often compensate for some design decisions that did not take into account human factors issues such as situation awareness. Consequently, effective experience feedback should be systematically implemented. Operational documentation could be easily customized as well as annotated and contextualized. Users should be more involved in the process of documentation evaluation. Active design documents are appropriate tools to support participatory design that involve designers, documentation specialists, training personnel and users. We believe that both experience feedback and participatory design should be supported by categorizations such the one presented in this paper.

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