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Cognitive Engineering in Training: Monitoring and Pilot-Automation Coordination in Complex Environments

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ABSTRACT

This paper reports our investigation of flight path monitoring in aviation. We interviewed experienced pilots to understand the knowledge and skills underlying effective monitoring and we developed an example learning environment to improve these skills. We explore how design of pilot training and learning, like the design of interfaces and of the underlying automation, benefits from cognitive engineering methods and perspective.

In aviation, monitoring and managing flight path are critical activities. The influences on flight path are complex and come from the autoflight system, from control actions by the pilot, and from external factors, including weather and Air Traffic Control (ATC). Indeed, inadequate flight path monitoring is a current aviation concern as it has been implicated in accidents and incidents. Effective piloting depends on strategies for noticing, understanding, and anticipating these influences to monitor and manage flight path. Lack of such skills reduces pilots' ability to maintain safety margin and resilience. Although flightdeck automation is intended to aid pilot understanding and prediction, the Fight Management Systems (FMS) can mislead as well as aid the pilot's understanding and projection of what will happen. In dynamic conditions, FMS predictions may be based on old or incomplete information. Understanding such vulnerabilities is an important part of pilot-autoflight coordination. The learning environment we developed is designed to help pilots proactively monitor and manage flight path. We consider how a broad cognitive engineering approach might inform the "what" and "how" of learning in dynamic work domains.

Keywords: Pilot monitoring, automation, learning, cognitive engineering, task analysis, work analysis, learning analysis, learning design, training, aviation.

INTRODUCTION

Our Problem: Understand Automation-Intensive Flight Path Monitoring

Piloting an airliner is fundamentally cognitive work. Using automation to manage and monitor flight path depends on a rich body of knowledge and skills. Current training methods, however, may not be well adapted to learning highly cognitive skills such as these. Further, the needed skills and knowledge are not well understood or specified. Indeed, inadequate flight path monitoring has been identified as a factor contributing to multiple accidents and incidents. We wanted to better understand monitoring in general, but particularly monitoring of flight path and its underlying knowledge and skills. In turn, such understanding might be used to improve learning.

Our Approach: Cognitive Engineering

Cognitive Engineering (CE) is a framework that helps design systems
for human use
that accomplish their intended function
within the relevant constraints and resources
when human cognition is a critical, central component.

It provides methods to analyze the constraints required by the work and how work is currently done, when relevant work exists (Roth, Patterson, Mumaw, 2002). This can identify current tasks, strategies, and the underlying skills and knowledge. CE methods include Cognitive Work Analysis (CWA) , Cognitive Task Analysis, and Critical Incident Reports (Klein, Calderwood, &Macgregor, 1989; Schraagen, Chipman, & Shalin, 2000;Vicente, 1999). Results of an analysis can then guide design of artifacts, such as automation, and other aspects of the sociotechnical system throughout the lifecycle (Sanderson, Naikar, Lintern & Goss, 1999).

We made use of this framework and the methods it offers after the physical and software components had been build and were in use. Specifically, we investigated how to support learning the cognitively demanding task of monitoring and managing the flight path of airliners.

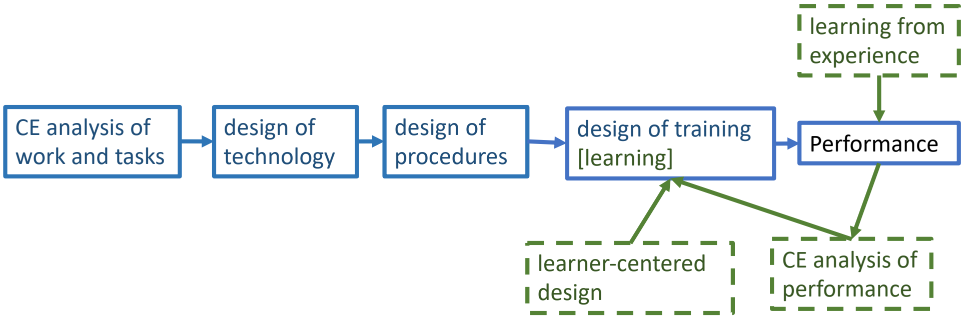

Figure 1. Blue boxes and arrows show an simplified schema of a frequent role of CE methods: inform the design of the software and hardware. This influence can then flow through the later-developed parts of the socio-technical system. Green dashed boxes and arrows show a feedback path "retrofitting" training and learning for an existing system using information about operational use, learning from experience, and a structured method for applying learner-centered design process and principles to content.

We wanted to know whether and how learning might be improved by understanding current performance on flight path management by effective pilots, and how this might inform design of learning, which, if implemented, might in turn improve performance. When Cognitive Engineering methods such as CWA are effectively applied, they frequently are "upstream" in the development process, as illustrated in Figure 1. Ideal use of CE is presented as being carried out prior to or early in the design and development of the sociotechnical system and then can pervade later phases. Broadly, the hardware and software design drives the procedures, which then drive training design. In our case, we were looking at a fully operational system to understand how highly skilled pilots monitor flight path, to identify knowledge and skills likely learned from experience rather than training, and to use this as feedback to design the learning environment and activities. Figure 1 provides a notional illustration.

IDENTIFYING CONTENT TO BE LEARNED USING CE INTERVIEW METHODS

Process- Opportunistic CWA

Our high level goal was to investigate how pilots carry out flight path monitoring and management. Ideally, the airplane follows the flight path programmed into the flight management system (FMS). Also, ideally, other factors, such as traffic or weather, do not force the airplane into a tactical change from the FMS flight plan. We wanted to understand the departures from this ideal scenario and how pilots monitored to anticipate and respond with pilot intervention, to alter automation flight modes and flight path targets as appropriate.

Our investigations were informal, constrained by what was feasible, and informed by CE methods. Our focus for investigation was descent using Standard Terminal Arrival Routes (STARs), our inquiry methods were interviews, and our interviewees were experienced line pilots.

Focus Phase of Flight. A STAR specifies a required vertical and lateral path as a series of waypoints with required altitudes and, often, airspeeds that transitions the airplane to a specific approach and runway. Descent, particularly in an approach done on a STAR, can be a challenging, complex phase of flight constrained by external and internal requirements. Externally, the physics of flight and the specific airplane performance limits impose energy management requirements that must be met while also meeting the STAR specifications. Internally, the flight path originally specified in the Flight Management System may need changes when the current context differs from the expected. Modes and targets may need to be changed. Managing the automation requires timely monitoring of the autoflight modes and targets and of the resulting flight path. Further, the autoflight system may make uncommanded mode changes. Understanding these constraints and how they make the work difficult is an important part of work analysis. The contribution of inadequate monitoring in descent to accidents and incidents further suggests that understanding this phase of flight will be particularly useful (Active Pilot Monitoring Working Group, 2014).

Interviewees: Selection criteria for pilot SMEs were informal. We sought out experienced pilots and looked for those who were also good at introspecting and articulating piloting processes. We interviewed a dozen pilots, half individually and half in a group setting.

Inquiry Methods. Observation in-flight or in simulators was not feasible. We used interviews drawing on CWA and CTA methods. Interviews were primarily face to face but some were remote. Some made use of pictures of flightdeck displays or flight charts both as prompts and to identify what the SME pilot was referring to. Interviews followed topics introduced by our SME pilots. Our interviews asked three broad types of questions. 1) What do you do on a "normal" STAR descent? Follow up questions asked about decisions made, the information needed and its source, and the strategies or heuristics used. 2) What is an example of a challenging descent (i.e., a critical incident) or a descent that makes it a 'hard day'? Follow-ups asked what was hard, what factors made it difficult, and how the situation was managed. 3) We asked about types of difficult descents generalizing from examples provided. These might be described in terms of the disruptive factor(s) and its impact based on time of occurrence. We built graphical representations that abstracted details to show how a type of event might unfold over time, including decision points (or "gates") and outcomes, to check our understanding of what the pilot SME reported.

In questions of type 2 and 3, we worked to identify what the constraints on successful descent were, including the timing and interactions among events. We did not push for reports of monitoring for exceptional, emergency conditions. It may be difficult to accurately recall high-stress, unusual situations. Questions including asking about what indications were monitored but shifted to discussion about the types of difficulties encountered. Questions were often reformulated; because we were asking about routine, even if challenging events, it sometimes took alternative framing to clarify our interest in descriptions of "just doing my job."

Product- Emerging view of FP monitoring

These interviews showed monitoring to be an active process of observing and making sense of the situation. We provided a model of monitoring to capture the types of behaviours our SME pilots described. To monitor, pilots build up and make use of a model of the situation; this guides attention and provides reference values for comparing current with expected values. The situation model includes relevant components of knowledge from long term memory about how systems work, such as models of how different autoflight modes work or how ATC usually manages different traffic flows. The situation model includes anticipation of what will happen, planning of needed pilot intervention, and prediction of the effects of different actions. For example, effective monitoring prior to the top of descent recognizes that the current mode is VNAV-ALT, that the airplane will not descend when cleared for descent in this mode, that the mode needs to be manually changed to VNAV-PTH, and that this should be stated to ensure both pilots have a shared model of the situation.

Monitoring involves a cycle of

- prioritizing a question or relevant information to obtain,
- obtaining and assessing the selected information, and
- identifying whether and what actions need to be taken.

Communication is needed both to report updates to the situation model and also to coordinate on the monitoring process itself. This sensemaking model treats monitoring as an active cycle of inquiry and is presented in brief (Billman, Mumaw, & Feary, 2020) and more extensively (Mumaw, Billman, & Feary, 2020). While the model does not address all aspects of monitoring, it provides a foundation for identifying many recurring components of monitoring that can be easily described and may be particularly learnable.

In addition, these interviews highlighted ATC changes to flight path as a particularly prevalent constraint adding complexity to the work of monitoring. Clearances that change the flight path to be followed deviate from the assumptions initially specified in the flight plan for the automation to execute. This may require include entering new target values in the autopilot system, assessing whether they would be feasible to comply with, whether mode should be changed, and whether the intended changes have in fact been entered and are in effect. We also obtained reports of various strategies for monitoring in particular types of situations.

Reported strategies varied greatly in specificity. They included quite general strategies about communicating expected upcoming events to the other pilot. Moderately general strategies addressed changing the autoflight modes and targets in a variety of conditions; modifying the automation was much more common that simply "turning it off", that is, switching to completely manual flight. (Turning off the autoflight system may be reported more often for more serious threats and may be produced by pilots less familiar with the details of automation than our pilots. A route-specific strategy directed the pilot to "find the ribbon of red lights," which is the Long Island Expressway, as a cue that you are nearing JFK. One flight-specific strategy was asking the PM to make sure the PF turned off the landing lights because the PF had forgotten this on the previous leg. Of course, this very specific strategy could be generalized to asking for special monitoring attention for any vulnerability specific to the current flight, but it was presented as a one-time occurrence.

Critically, pilots stated that the skills and knowledge they were reporting had not been trained. Rather, it had been learned from experience.

The understanding developed from these interviews was used in an exploratory training study (Billman,,,), which found modest but reliable effects of training in a simple test-retest design. Further, it set the stage for a more principled design of learning materials.

BUILDING A LEARNING MODULE USING LEARNING-DESIGN METHODS

Process: Method for Learner-Centric Design

Using a systematic design for learning, we produced a web-based training module designed to help pilots perform adaptive flight path monitoring behaviors. This system organizes the content for learning into a hierarchy of intellectual skills. The system provides a flexible platform for integrating a task analysis, learner analysis, and goal analysis to attain a terminal goal of demonstrating proactive pilot monitoring behaviors in a specified context. We applied the Dick and Carey design model to integrate three proactive flightpath monitoring activities into a learner-centric intervention (Dick, Carey,&Carey, 2015). The design uses interactive webtools to: 1) Permit integration and practice of the Sensemaking Model for monitoring flight path management, 2) Practice a strategy for analyzing standard terminal arrivals (STARs) for flightpath management threats, and 3) Demonstrate measurable crew communication behaviors that support proactive and adaptive monitoring activities.

Taking the learners’ cognitive and affective characteristics into account, the current design provides context and practice for behaviors that let operators adapt to a operational environment that was only partially designed with human factors considerations in mind. Focusing on learning goal-oriented actions, and not procedural steps, creates a human-centered system with multiple paths to the final learning objective. Each sub-skill is measurable and adjusted to the target audience. As the operational context evolves, such a systematic design enables modifying the hierarchy to address the revised problem space. Finally, since the learning system measures performance outcomes at each sub-component in the hierarchy, gaps in performance in a mid-level or terminal objective can be linked to performance gaps in the subordinate skills, indicating areas where the designed learning intervention needs adjustment to support learner performance.

Content of Learning

This learning intervention addresses monitoring in the specific context of flying STARs. It begins by demonstrating the benefit of anticipatory work to develop adaptive pilot monitoring behaviors. In the second section, the learners demonstrate that they recognize monitoring is in part an anticipatory behavior. In a narrated real-world scenario, the learners practice asking questions about the future state of the aircraft. For example, learners are presented with a task of setting a target for flight path monitoring against which to compare the aircraft state as the situation evolves. If they select an option that does not involve the future state of the aircraft they receive corrective feedback. The third section presents a model for making sense of an evolving situation through the Sensemaking Model; an iterative, three-component process:

1) Asking questions about the future state of the aircraft,
2) Gathering relevant information to answer these questions,
3) Deciding on an action that best responds to the situation as the crew understands it.

The learner demonstrates applying this model to a flightpath monitoring situation involving internal and external cueing of flightpath management challenges. The fourth section conveys a strategy to analyze a STAR to identify any flight segments that can pose an energy management threat. Finally, the module conveys three general communication behaviors that enable a crew to collaboratively and proactively perform the monitoring strategies proposed in the module. The design scaffolds the content in a set of real-world challenges familiar to transport category pilots.

Learners work through a progression of intellectual skills to recognize, demonstrate, analyze, and apply subordinate skills. They emerge with an adaptive monitoring strategy understood to improve flight path monitoring performance in different flight conditions. A future simulator study may validate the impact of these strategies and explore the possibility of transfer across contexts.

Principles Supporting the Learning Process

To promote learning by activating relevant cognitive structures (Merrill, 2009), learners interact with the module to recall and demonstrate prior knowledge associated with the targeted intellectual skills. Using interactive software embedded in the website, presentations pause at strategic points within the real-world scenarios and present the learner with questions about their own experiences and attitudes relating to the scenario. The questions sets provide feedback that varies depending on the learners' response. These activities are designed to integrate these mental models into the learners' personal experience.

Example Activities Illustrating Learning Principles.

In accordance with Mayer's Redundancy, Voice, and Personalization Principles (Mayer, 2009), a natural voice narration accompanies simple graphics depicting the vertical path of aircraft as pilots progress along a STAR (see Figure 2).

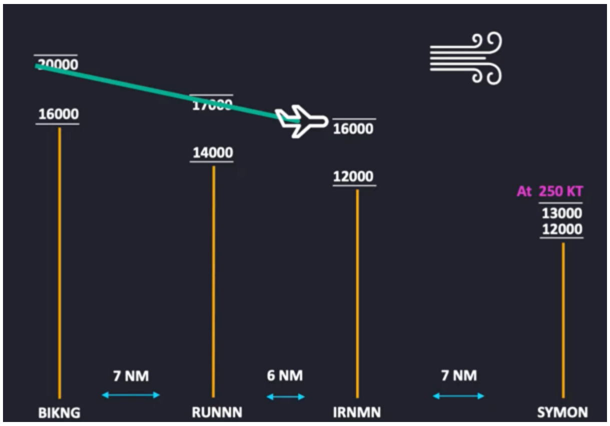

Figure 2. Animation showing vertical profile of airplane flight path with STAR altitudes and distances between way points.

Two examples illustrate how the module implements some of the learning principles. Throughout the module, questions are designed to promote learner reflection on their own experiences in accordance with Merrill's Integration Principle. Real-world scenarios allow users to recall prior knowledge and integrate the intellectual skills into their own experiences. In the section designed to have the learners understand the value of anticipatory behaviors when preparing for a complex flight operation, the learner steps through and is asked about events in a scenario when ATC issues a clearance that adds energy to the flight by delaying descent. As the narrative of the flight unfolds, the video pauses at key points to ask questions such as: "What will the FMS do to attempt to comply with the constraint?" followed by: "Is there anything the crew could have done in advance help the auto flight system comply with the constraint?" And later: "As PM, have you ever waited too long for the PF to address a flight path management issue?"

Having reflected on experiences where anticipating threats enables crews to create desirable operational outcomes, a later section depicts another real-world scenario that activates the learners' prior knowledge, while the helping build the appropriate mental model (Merrill, 2009) As this scenario evolves the presentation pauses, and the learner is asked what question the crew could ask about the future state of the aircraft to understand the impact of an ATC clearance. The learner faces three options familiar to inquisitive pilots: Is a tailwind impacting them? Are they encroaching on preceding traffic? The third, most relevant option asks what altitude the flight must cross a downrange waypoint in order to meet a final crossing restriction. If the learners choose the distractor questions, they receive a commentary box describing why the chosen answer doesn't help predict the future state of the aircraft, as well as an additional commentary box describing why the final selection creates a flight path monitoring objective useful in analyzing the flight's progress relative to the desired state.

SUMMARY AND CONCLUSIONS

Summary

Our problem concerned analysis and design for learning, where the socio-technical system was build and in use. We drew on the user-centered framework of Cognitive Engineering and the various associated interview methods to investigate monitoring of flight path and how the needed knowledge and skills might be learned. Observing actual or simulated flight was not feasible. However, discussion with a considerable number of expert pilots provided valuable insight to the processes and strategies used in monitoring flight path. Indeed, for highly cognitive work it may be particularly valuable to have self -report, not only observational data.

Interaction with automation was a pervasive element of these experts' descriptions. The prevalence of anticipation, comparison, and planning for possible events highlighted the proactive nature of monitoring. The interviews informed a model of monitoring that characterizes the proactive, investigatory nature of monitoring, particularly for flight path management. Pilots commented that they learned about monitoring though experience, not just training. This provided encouragement that examination of what effective pilots knew could usefully inform design of a learning environment.

This work was substantially expanded through use of an established, validated method for design of learning environments. This provided a method for identifying and organizing the content, or learning objectives, and providing a set of vetted principles that facilitate learning and can be used in design.

Limitations

Empirically we were limited in lack of access to real time performance. In particular, we did not gain insight into the timing of perceptions and actions as they might affect monitoring. Further our scope of inquiry focused on one phase of flight, and emphasize the specific context of descent using STARs. While this context is particularly complex, and effective monitoring of flight path particularly challenging, there are many other situations for monitoring flight path. We were also limited in the resources for developing the learning module. In particular, future revisions might benefit from additional development of interactives and feedback.

Future work

Summative evaluation will be done on with web-based and then simulator-based delivery. Evaluation will include cognitive and affective domain components, exploring the what participants learned by measuring how well and how often the participants applied the content in the learning objectives. Simulator evaluation offers a broader range of observable measures and has a greatly expanded scope compared to the web-based learning evaluation. Observable behavior markers include intra-crew communication, control actions, and autoflight selections. These activities drive aircraft path outcomes as the crew respond to external influences such as ATC clearances, challenging arrival geometries, and winds that complicate flight path management goals. In turn, evaluation of effectiveness of the learning modules will inform further development.

Conclusions

This work contributes an expanding view of monitoring, which emphasized the proactive, anticipatory process of building, sharing, and updating a situation model. It provided a less common application of cognitive engineering approaches, looking at design of learning environments for an in-operation system, rather that early input to design of software or hardware. This work also contributes an expanded view technology support for learning. It adopts a learner-centered perspective of designing for learning, rather than the institutional perspective implicit in training. It also provides a method for identifying skills and knowledge of expert users and provides learning opportunities to speed the development of expertise across the pilot community and across monitoring challenges.

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