Combining Two Technologies to Improve Aviation Training Design

Marilyn Hughes Blackmon and Peter G. Polson

Institute of Cognitive Science, University of Colorado
Boulder, CO 80309-0344 USA
{blackmon, ppolson}@psych.colorado.edu

Abstract

Combining two recent technologies can markedly improve the performance outcomes and cost-effectiveness of aviation training. The first is a well-tested design methodology for developing cognitive tutors (Anderson et al. 1995, Anderson and Schunn 2000) based on modern theories of skill acquisition. The second is the advent of high-fidelity PC-based part-task simulators on which pilots can "learn by doing" and "progress to real-world performance," two essential guidelines for designing cognitive tutors. An experimental flightcrew automation training program (McLennan et al. submitted) produced results consistent with non-aviation training results using Anderson's cognitive tutors, implying that pilots trained on cognitive tutors can attain the same or higher level of competence in approximately one-third the training time for traditionally trained pilots.

Introduction

There is widespread agreement that training programs for glass cockpit commercial transports need to add more topics, including information about the organization and logic of the Flight Management System (FMS) and training on a wider range of necessary programming and decision making skills (Air Transport Association 1997, 1998, 1999; FAA 1996). However, intense economic pressures on the airline industry inhibit the development of more comprehensive, longer, and more expensive training programs (FAA 1996). The goal of this paper is to describe two technologies that will enable the industry to increase both the depth and breadth of automation training within current training program footprints, designing and delivering training programs that ensure high performance and are much more time- and cost-efficient.

The two technologies are (a) *cognitive tutors* – adaptive, computer-based instruction systems – developed by Anderson and other researchers at Carnegie-Mellon University (Anderson et al. 1995; Anderson & Schunn, 2001), and (b) high fidelity, part task-simulations of modern autoflight systems hosted on desktop and laptop PCs (Aerosim Technologies, www.aerosim.com; Tricom Technologies, www.tricom-tech.com/products.htm, CAE, www.cae.com; and Wicat, www.wicat.com).

Using the lesson planning mechanisms built into these PC-based part-task simulators will be the ideal and easiest way to combine the two technologies, as soon as manufacturers of these simulators incorporate full support for Anderson's guidelines into the lesson planners of their simulators. For the interim we conducted an experimental pilot training study (McLennan et al., submitted) that combined the two technologies using only an early, low-fidelity PC-based part-task simulator and a patchwork of instructional methods (e.g., CBTs, part-task trainers) that are already familiar to, and widely used by, the aviation community. Thus, there is a pragmatic solution that can be implemented without delay: integrating PC-based part-task simulators with cognitive tutors designed to adhere to Anderson's guidelines.

Our training study (McLennan et al., submitted) offers proof-of-concept to verify our hypothesis: that if pilots are trained on a cognitive tutor that adheres to Anderson's guidelines and is integrated with even a primitive simulator, these pilots can attain the same or higher level of competence in approximately one-third the training time for traditionally trained pilots. Our hypothesis was based on accumulated results from mature cognitive tutors developed by Anderson and his colleagues. These tutors were designed to optimize learning rate for high school mathematics and college-level computer programming courses compared to the learning rate of control students taught in conventional classrooms. Students taught on these cognitive tutors reliably capture "at least the same level of mastery as control students in about one third of the time" (Anderson 1993, p. 236).

We structure this paper around seven guidelines for designing cognitive tutors (Anderson et al. 1995, Corbett, Koedinger, and Anderson 1997), presenting first the three guidelines that have, in our estimation, the greatest value for reaping time- and cost-savings for aviation training. In each section we explain how to design aviation training to adhere to the specific guideline. We also outline the role that a PC-based part-task simulator should play to augment the benefits of applying that guideline. In addition, in each section we offer examples and cite supporting evidence from our own experimental pilot training study (McLennan et al. submitted), referred to in the balance of the paper as the "McLennan Training Study."

Build Goal-Method Model of Competence

The aviation community is no stranger to the value of representing aviation competencies with fine-grained cognitive task analyses. The Advanced Qualification Program (AQP) mandates the use of job task analysis and subtask

---

analysis for curriculum development (Longridge 2000), and aviation trainers increasingly rely on cognitive task analysis for developing aircrew training programs, for designing automated aviation systems, and for managing human resources (see extended reviews in Schraagen, Chipman, and Shalin 2000; Seamster, Redding, and Kaempf 1997).

Anderson's first guideline specifies using the products of a detailed cognitive task analysis to build a psychologically valid, formal goal-method model of all the skills to be acquired in training – the targeted competence (Corbett, Koedinger, and Anderson 1997). In addition to meeting or exceeding the AQP standards, a psychologically valid goal-method model aligns with modern theories of skill acquisition. The term "goal" refers to the intention to perform a task, and a "method" is a sequence of steps for accomplishing a goal. The goal-method model has a hierarchical goal structure. Each individual step in a method either sets a subgoal or stipulates performing a simple physical/mental action. High-level goals are usually accomplished primarily by setting subgoals, but the lowest-level subgoals specify only simple physical/mental actions.

The hierarchical goal structure of the model is necessary for accurately representing the goal-driven nature of human skilled behavior. In the actual performance of a skill, each goal/subgoal provides a necessary retrieval cue that triggers performance of a specific action. As a result, a highly skilled person smoothly performs appropriate actions in response to each particular situation, and each action is triggered by the presence in working memory of both the necessary goal and the necessary condition(s) in the situation. Skill-acquisition theorists express this using formal *if-then* or *condition-action* rules: "If goal(s) and if particular condition(s) in working memory, then perform specific action." For example, if the goal is to comply with an ATC directive, and if the Navigation Display shows that the conditions make it feasible for the pilot to comply with the directive, then the pilot sets a series of subgoals. The pilot then performs the actions to accomplish the subgoals and thereby smoothly accomplishes the goal of complying with the ATC directive.

There are various options for formatting the goal-method model. If the training involves building an intelligent tutor, then the goal-method model must be a production system, i.e., a computer program composed of a large number of fine-grained condition-action rules. Otherwise, a simpler option is to build a detailed NGOMSL model, the option we used in the McLennan Training Study. NGOMSL is one variant of the well-known family of GOMS methods (Kieras, 1997; John & Kieras, 1996a, 1996b). An NGOMSL analyst does a top-down decomposition that starts with the top-level and higher-level goals and methods, continues down through intermediate-level and lower-level subgoals and methods, and finally ends with the lowest-level subgoals and methods. NGOMSL uses natural language and can be learned without prerequisite computer programming skills or graduate training in cognitive psychology. The McLennan Training Study verified that aviation trainers and curriculum designers can quite quickly learn to build NGOMSL models.

Need *Complete* Model

The goal-method model defines the curriculum for the training, and it is crucial that the model be a complete, fine-grained analysis, specifying the detailed sequences of physical actions and mental operations necessary to carry out each and every specific task required for competent skilled performance. Since pilots frequently monitor, comprehend, and interact with various displays and other cockpit hardware, the complete model must contain clear specifications of all of these mental/physical actions.

Errors in performing a skill are often caused by missing pieces of knowledge, i.e., missing condition-action rules (Anderson 1993, 245). If the model is incomplete the curriculum defined by the model will be incomplete, and, as a result, people trained on that curriculum will generally end up with missing pieces and be prone to errors. Thus, to prevent human error in safety critical situations it is crucial to construct a complete model of competence.

In the McLennan Training Study, for example, we traced performance errors of experimentally trained pilots to a few missing pieces in our model. The model described the goals/subgoals accomplished by expert pilots when programming the Control Display Unit (CDU) interface to the Flight Management System for selected CDU tasks. We limited our model and training to CDU tasks tested on the FAA-mandated checkride for pilots transitioning to an advanced automated aircraft. Our model proved incomplete for some steps involving the Navigation Display (ND), probably a consequence of our inadequate ND simulation.

Identifying Core Subgoals Used to Do Many Tasks

Payoffs for building the complete goal-method model are quickly apparent. First, the model facilitates discovery of core intermediate-level subgoals that are repeatedly called by the various methods for accomplishing many or most higher-level goals. These core subgoals (and the methods for accomplishing them) are a major source of transfer and create the potential to save training time – assuming the training curriculum encourages transfer by drawing learners' attention to these core subgoals.

Discovering core subgoals repeated across diverse tasks has deep implications for training. Instead of teaching each task as a rote sequence of keystrokes and their related mental operations, pilots are trained to recognize when to accomplish each subgoal. Pilots master various methods to accomplish each subgoal in slightly different contexts. Each subgoal method substitutes for a block of keystrokes and linked mental operations. The instructional materials must emphasize these core subgoals and their associated methods throughout the training process, eliciting transfer of training across all the diverse tasks that call these core subgoals. Intermediate-level subgoals can, in turn, call lower-level subgoals.

In the McLennan Training Study, for example, our NGOMSL model identified three intermediate-level subgoals that were needed to accomplish almost every higher-level goal that involved use of the Control and Display Unit (CDU), and each of these three intermediate-level subgoals called lower-level subgoals.

Grouping Related Tasks under Higher-Level Goal

Another important insight that can emerge from a NGOSML analysis is to find highly similar tasks that can optimally be taught as distinct methods for accomplishing a single higher-level goal, not as isolated, unrelated tasks (the way these tasks are often presented in conventional training programs). When methods are very similar, grouping them together draws attention to the similarities, fostering transfer of training and thereby reducing training time. Just as important, grouping these similar tasks under a single higher-level goal highlights the distinctive components of each method, not just the similarities.

For example, in the McLennan Training Study the distinctive features for eight similar methods correspond to eight similar but distinct Air Traffic Control (ATC) directives. Each of the eight similar but distinct methods accomplishes a single higher-level goal, **Modify Route**. The vast majority of tasks in flight are driven by communication from ATC in the form of directives to change the originally cleared routing. Teaching pilots the eight tasks as eight methods for accomplishing a single goal – **Modify Route** – results in pilots rapidly mastering the subtle distinctions among similar ATC directives and reliably responding with the correct method in response to each distinct ATC directive.

Learning by Doing Essential to Acquire Skill

The second guideline for developing cognitive tutors – ensuring that pilots learn by doing from the outset of training – is one of the most significant for the aviation community. Aviation training programs are too often based on the mistaken assumption that pilots can and must start by learning a large amount of prerequisite textbook knowledge, leaving a time gap before pilots have the chance to actually do all the tasks learned about in the text.

To acquire a skill, the learner must convert declarative knowledge (*knowing about*) to condition-action rules (procedural knowledge, *knowing how to*). The conversion must occur while actually doing the task. Learners need highly pertinent, just-in-time declarative knowledge while trying to understand *how to do* the worked-out example problems and then reinforce the new skill by practicing doing similar problems. Whenever there is a significant delay between learning the requisite declarative knowledge and acquiring the skill, the learner has forgotten essential knowledge and must relearn it at the time of genuinely acquiring the skill as condition-action rules. Pilots in some cases do not learn *how to do* a task until they begin practicing in fixed-base/full-motion simulators, raising training costs by unnecessarily prolonging simulator time.

At the outset of training pilots should be learning the low-level subgoals and associated methods as procedural knowledge and then repeatedly practicing the skills to strengthen them (Anderson and Lebiere 1998, Chap. 2 and 4). Subsequently pilots should move on to acquiring the intermediate-level subgoals and methods and then the higher-level goals and methods. In all cases it should be learning by doing, moving as rapidly as possible to the higher-level goals and methods practiced in realistic flight scenarios. Since higher-level goals set lower- and intermediate-level goals, pilots are actually practicing all levels of goals whenever they are engaged in accomplishing the higher-level goals.

PC-based part-task simulators are essential for learning by doing. A high-fidelity PC-based part-task simulator allows pilots to practice accomplishing goals incorporating mental/physical actions on the simulator in the same way that these actions are done on the actual cockpit hardware. Condition-action rules have the form, “If goal(s) and condition(s)/situation(s), then do method X.” By learning to recognize the goals and conditions in the context of a high-fidelity simulation of one or more cockpit devices, a pilot is more apt to react appropriately in a comparable actual flight situation. In the McLennan Training Study, for example, simulation of the Navigation Display (ND) used during training did not have adequate fidelity. Pilots were unable to master those CDU tasks that involve the ND until they could practice on the ND in the full-motion simulator during the transfer test, marring their test performance.

According to modern skill-acquisition theory, skills acquired by the end of training can be virtually identical if all learners solved the same set of problems, regardless of whether pilots learned by solving these problems in a full-motion simulator, a fixed-base simulator, or on part-task trainers. Acquisition of the required set of condition-action rules results in identical performance of the same skill regardless of the learning environment. Practice tasks should be performed on high-fidelity PC-based part-task simulators whenever possible, reserving expensive fixed-base/full-motion simulators for the final integration of separately learned skills. Expensive simulators are needed only for doing the most realistic flight scenarios with demands for multi-tasking and adapting skills to handle novel situations.

Provide Immediate Error Feedback

The third guideline – providing immediate error feedback – is absolutely essential for sharply reducing training time. Error feedback ensures acquisition of all pieces of knowledge represented in the complete model of competence.

The phrase “immediate error feedback” requires further explanation. Anderson recommends administering feedback incrementally in three or four stages. The first hint should be just a reminder of the goal. It is critical not to interrupt pilots and their current working-memory state to point out minor errors. If the first-stage help message is not enough, the second should describe the relevant features of the current situation and the final goal. A third hint, if needed, can provide the rule for moving from the current state in the problem space towards the end goal. Only as a last resort should the help message describe a concrete action(s) to take. The lesson planner software must, therefore, allow the programmer to specify the order in which error messages will appear, presenting different kinds of feedback depending on whether the error is the first, second, third, or fourth incorrect response to a requested action, or a delay.

Providing feedback in incremental stages also makes allowances for important aptitude-treatment interactions. Students with strong background knowledge benefit most from the second-level help messages, while students with weak background knowledge benefit most from third-level help messages. In addition, limiting the feedback to signaling the presence of the error (without commenting on it, diagnosing it, or providing the correct solution) gives the student a sense of control, stimulating independent thinking that improves performance outcomes and transfer.

An experiment reported by Anderson (Anderson 1993, Anderson and Lebiere 1998) clearly demonstrated the value of immediate error feedback by comparing student performance learning to do LISP programming on a cognitive tutor under four different tutoring modalities. Students in the immediate-feedback modality completed the tasks in the least amount of time. Students in the no-feedback modality took about three times as long as students in the immediate feedback modality. Students in the feedback-on-demand modality took about twice as long. Students in the error-flagging modality had the freedom to either ignore the error feedback or request the tutor's error message, and they took nearly twice as long. Despite these marked differences in time expended on solving the same set of problems, the performance of all four groups was virtually the same after the groups had finished solving all the problems. The underlying reason is that solving all the problems resulted in acquiring the same set of condition-action rules, which, in turn, resulted in equivalent performance.

Freeplay tutors are often used with no error feedback mechanisms. Freeplay tutors have the merit of supporting learning by doing, but the absence of error feedback makes very inefficient use of pilots' valuable time. PC-based part-task simulators need to be used in combination with immediate error feedback. Lesson planners currently built into these simulators do make some provisions for error feedback but only partially comply with this guideline.

Gradually Increase Grain Size of Instruction

Another valuable guideline for building cognitive tutors is to gradually increase the grain size of instruction – an implication of the hierarchical goal structure of skilled performance. The analyst constructed the goal-method model of competence top-down, starting with the highest-level goals and decomposing them down to lower- and lower-level goals. The training design, however, moves in the opposite direction. Flightcrew need to first learn to accomplish low-level goals and gradually work up to the complex methods required for accomplishing high-level goals. When students move up to learning to accomplish intermediate-level goals, they continue practicing what they learned earlier, because the methods for accomplishing intermediate-level goals set subgoals to accomplish the lower-level goals they previously mastered. The grain size grows even larger when learning methods to accomplish high-level goals. These complex methods set subgoals to accomplish intermediate-level goals, which, in turn, specify accomplishing low-level goals. The McLennan Training Study exactly followed this plan.

Current PC-based part-task simulators generally mesh well with the guideline to gradually increase grain size of the instruction. Typically these simulators can be set to show just one cockpit device at a time, allowing pilots to be given bottom-up, part-task training and focus on one particular cockpit device at a time. Pilots later can advance to doing more complex tasks that involve coordinating interactions with two or more cockpit devices on the simulator. Early in training it would be distracting and confusing if pilots had access to multiple cockpit devices, but when pilots are ready to begin integrating all their skills to perform realistic flight scenarios, simulators can be set to interact with a complete set of cockpit hardware.

Clearly Communicate the Goal Structure

Another guideline is to focus learners' attention on the hierarchical goal structure of the task. The hierarchical goal structure transmitted during training comes from the goal-method model that drives the curriculum. A cognitive tutor can communicate the goal structure by explicitly representing the current goal (e.g., on the computer screen) and/or by communicating the current goal through help messages. According to modern theories of skill acquisition and expertise, performance of skills is goal driven, not driven by memorized sequences of steps. In actual performance, an expert pilot must respond to a goal by setting the right subgoals and then applying the right method to accomplish each subgoal.

For example, when building a NGOMSL model the McLennan Training Study found that all CDU programming tasks require setting three subgoals: **ACCESS**, **DESIGNATE**, and **INSERT**. From the outset of training our computer-based cognitive tutor taught and reinforced the goal structure. Instead of learning each CDU task as a separate sequence of up to 18 keystrokes, the cognitive tutor emphasized formulation of correct goals in response to ATC directives before pressing any keys. The tutor displayed the name of the goal in red font on the computer screen, prompting learners to **ACCESS** the appropriate area, then **DESIGNATE** the appropriate route element or information, and then **INSERT** that information on the correct line (each time the program waited for the correct response). Error feedback, when needed, reminded the learner of the current goal. If that reminder proved insufficient, the cognitive tutor offered hints about how to accomplish the goal.

The PC-based part-task simulator is an important element for the communication of the goal structure. Pilots must be able to set and accomplish goals and subgoals in realistic flight scenarios, knowing how to react to both routine situations and emergency situations caused by bad weather or equipment failures. The way to do this is to integrate the communication of the goal structure with presentation of the goals/subgoals in the context of realistic flight scenarios on the PC-based part-task simulator. Pilots then learn to set and accomplish goals in the context of recognizing patterns of conditions while monitoring the Navigation Display and maintaining situation awareness.

Increase Transfer to Novel Problems

Another important guideline for designing cognitive tutors is to foster transfer of skills to novel problems by promoting acquisition of skills that are sufficiently general to solve a broad class of problems. Free-play tutors (e.g., Sherman and Helmreich 1998) let learners select the problems, but that approach is inefficient and ineffective. The training needs to present a well-chosen set of problems that systematically cover all skill components. Pilots need to practice enough different variants of each task (e.g., the CDU task “Intercept Leg-to”) to become able to recognize instances of each task in novel contexts.

A consistent finding in the research literature on skill acquisition is that learners tend to develop overly specific knowledge that transfers poorly if they (a) learn a rote sequence of procedures, (b) study a single example problem, and/or (c) limit practice to a set of highly similar problems. When learners relate specific problem-solving experiences to the underlying abstract principles that structure and integrate the domain, they become able to solve hard novel, far-transfer problems (Anderson 1993).

The McLennan Training Study complied with this principle by using two strategies. First, realistic flight scenarios posed a diverse array of practice problems, encouraging pilots to encode procedures general enough to cope with almost any instance of that CDU task that they might ever encounter. Second, the training connected the newly acquired set of CDU skills to pilots’ previously acquired higher-level knowledge by nesting the goal structure for the CDU skills within the larger context of the multi-tasking cockpit environment. For example, teaching pilots **Modify Route** tasks integrated pilots’ CDU skills with their knowledge of ATC directives.

Progress to Real-World Performance

Another guideline is to have learners practice solving real-world problems and to gradually reduce scaffolding assistance from the cognitive tutor so that learners progress to real-world performance relying only on real-world feedback. Airlines already do an excellent job of this, providing much practice in fixed-base and full-motion simulators that closely approximate the multi-tasking demands of actual flight situations. Airlines give pilots extensive practice coping with unusual situations, such as safety hazards posed by weather conditions or equipment failures. The question remains, however, whether airlines could comply with this guideline more cost-effectively.

In the McLennan Training Study experimentally trained pilots were advanced to performing real-world CDU tasks in only five hours of training time. Experimentally trained pilots rapidly moved to accomplishing the **Modify Route** goal in response to inflight ATC directives for a wide variety of realistic flight scenarios with little or no assistance from the tutor. These higher-level tasks are representative of those on which transitioning pilots must perform well during the FAA check ride. Using realistic flight scenarios is a crucial guideline for designing part-task trainers for use in aviation training (Eurocontrol 2000). State-of-the-art PC-based part-task simulators allow pilots to perform tasks using all cockpit equipment, better than the low-fidelity simulators.

At the end of training, the McLennan Training Study compared the performance of the 19 experimentally trained pilots to a group of 19 traditionally trained pilots that had just completed transition training for the same aircraft. All pilots were given a demanding real-world transfer test in a full-motion simulator, utilizing a realistic line oriented flight training (LOFT) scenario. Pilots were tested individually. First the pilot performed the preflight CDU tasks and then, while airborne on the simulated flight, the pilot had to respond to ATC directives to modify the route.

We have deliberately avoided burdening this paper with details of the experimental design and statistical analyses reported elsewhere (McLennan et al. submitted). In a nutshell, the performance of the experimentally trained group was equivalent in accuracy to the traditionally trained pilots, but experimentally trained pilots had invested only five hours in learning the CDU tasks – only about one-sixth as much training time on the CDU tasks as traditionally trained pilots. We argue that if experimentally trained pilots had spent another five hours practicing, and if that practice had been on a higher-fidelity PC-based part-task simulator, then the experimentally trained pilots would have speeded up enough to be comparable to traditionally trained pilots in performance times as well as accuracy. In other words, the experimentally trained pilots in our study would have reached the same or better performance in one-third the training time – consistent with the performance outcomes from mature cognitive tutors in Anderson’s lab.

Conclusions

We have argued here that markedly improved, cost-effective flightcrew training can be devised by integrating Anderson’s guidelines for designing cognitive tutors into the lesson planners of PC-based part-task simulators.

Proof-of concept for the effectiveness of this combination has been drawn from the McLennan Training Study. This aviation-specific evidence is bolstered by an extensive body of research on other cognitive tutors designed to comply with Anderson's guidelines, research on skill acquisition, and research on PC-based part-task simulators in aviation training (Salas, Bowers, and Prince 1998).

We have structured this presentation around Anderson's guidelines and showed that both airline training and PC-part-task based simulators already comply quite well with some guidelines. Full compliance with several of Anderson's guidelines would, however, require significant changes in current aviation training practice and redesign of some features of the lesson planning software built into current PC-based part-task simulators. The changes required to fully implement and integrate the two new technologies do not conflict with current practice. Rather, the changes would actually improve the internal consistency of current practice and its underlying theory, and the effort of making the changes would be rewarded by significant increases in the cost-efficiency and performance outcomes of flightcrew training.

Acknowledgments

This research was supported by the National Aeronautics and Space Administration under Cooperative Agreement NCC 2-1104 and NSF Grant CISE/EIA-0137759 with the University of Colorado. The authors would like to thank the following individuals for their contributions: Lance Sherry, Everett Palmer, and Mike Feary.

References

Air Transport Association. 1997. Towards an Operational Philosophy and Model Training Program for FMC-Generation Aircraft (First report by the Human Factors Committee Automation Subcommittee). Request copy of this report by e-mail to Tom_Chidester@amrcorp.com.

Air Transport Association. 1998. Potential Knowledge, Policy or Training Gaps Regarding Operation of FMS-Generation Aircraft (Second report by the Human Factors Committee Automation Subcommittee). Request copy of this report by e-mail to Tom_Chidester@amrcorp.com.

Air Transport Association. 1999. Performance of Standard Navigation Tasks by FMS-Generation Aircraft (Third report by the Human Factors Committee Automation Subcommittee). Request copy of this report by e-mail to Tom_Chidester@amrcorp.com.

Anderson, J. R. 1993. *Rules of the Mind.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Anderson, J. R., Corbett, A. T., Koedinger, K. R., and Pelletier, R. 1995. Cognitive Tutors: Lessons Learned. *The Journal of the Learning Sciences 4*, 167-207.

Anderson, J. R., and Lebiere, C. 1998. *The Atomic Components of Thought.* Mahwah, NJ: Lawrence Erlbaum Associates.

Anderson, J. R., and Schunn, C. D. 2000. Implications of the ACT-R Learning Theory: No Magic Bullets. In R.

Glaser, ed., *Advances in Instructional Psychology: Vol. 5. Educational Design and Cognitive Science,* 1-33. Mahwah, NJ: Lawrence Erlbaum.

Corbett, A. T., Koedinger, K. R., and Anderson, J. R. 1997. Intelligent Tutoring Systems. In M. Helander, T. K. Landauer, and P. Prabhu, eds., *Handbook of Human-Computer Interaction* (2^{nd}, completely revised edition, 849-874). Amsterdam: Elsevier.

Eurocontrol. 2000. Guidelines for the Production of Computer Based Training. Available on the Web at http://www.eurocontrol.be/projects/ians/cbtguidelines/html/body_index.html.

Federal Aviation Administration (FAA) Human Factors Team. 1996. *Report on the Interfaces between Flightcrews and Modern Flight Deck Systems* (June 18, 1996). Washington: U.S. Department of Transportation, Federal Aviation Administration.

John, B. E., and Kieras, D. E. 1996a. Using GOMS for User Interface Design and Evaluation: Which Technique? *ACM Transactions on Computer-Human Interaction 3*(4), 287-319.

John, B. E., and Kieras, D. E. 1996b. The GOMS Family of User Interface Analysis Techniques: Comparison and Contrast. *ACM Transactions on Computer-Human Interaction 3*(4), 320-351.

Kieras, D. 1997. A Guide to GOMS Model Usability Evaluation Using NGOMSL. In M. G. Helander, T. K. Landauer, and P. V. Prabhu (Eds.), *Handbook of Human-Computer Interaction* (2^{nd} rev. ed., 733-766). Amsterdam: Elsevier.

Longridge, T. M. 2000. Overview of the Advanced Qualification Program. Available on the Federal Aviation Administration website at http://www.faa.gov/avr/afs/tlpaper.htm.

McLennan, S., Irving, J. E., Polson, P. G., and Blackmon, M. H. Submitted to *International Journal of Aviation Psychology*. Experimental Evidence Favoring Adoption of Cognitive Tutors for Flightcrew-Automation Training.

Salas, E., Bowers, C.A., and Prince, C. eds. 1998. Special Issue: Simulation and Training in Aviation. *International Journal of Aviation Psychology 8*(3).

Schraagen, J. M., Chipman, S. F., and Shalin, V. L. eds. 2000. *Cognitive Task Analysis.* Mahwah, NJ: Lawrence Erlbaum Associates.

Seamster, T. L., Redding, R. E., and Kaempf, G. L. 1997. *Applied Cognitive Task Analysis in Aviation.* Aldershot, UK and Brookfield, VT: Avebury Aviation.

Sherman, P. J., and Helmreich, R. L. 1998. Training for Use of Automation: The Value of "Free-play" as a Complement to Traditional Transition Training. In *Proceedings of the Ninth International Symposium on Aviation Psychology*, 243-248. Columbus, OH: The Ohio State University.