Cognitive Fidelity in the Design of a Maintenance Troubleshooting Trainer

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ABSTRACT

Previous papers have explored the concept of cognitive fidelity and its application to training in decision-making skills. These papers have described the concept of cognitive fidelity and its value in ensuring the realism of information as an essential factor in decision-making training. Devices designed for high cognitive fidelity would provide a user with highly realistic information, but might not require a physical environment of corresponding realism.

This paper reports on the design and development of a device for training the troubleshooting of an aircraft fuel system. The paper's initial focus is on the design choices made to ensure that cognitive fidelity remained high under conditions which sharply constrained physical fidelity. The paper shows how the functional requirements of specific training objectives were used as a basis for design specifications.

The development of the troubleshooting trainer is described, identifying the key design choices, and the way in which cognitive fidelity was used as the basis for selecting between specific design alternatives. Specific features examined include simulation of test procedures, simulation of related systems, and trainee interface.

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INTRODUCTION

Training environments employing simulation traditionally have been made as realistic as technology would allow, with designers taking every opportunity to add any feature of the task environment which could be represented. The effectiveness of this approach is inarguable, and for jobs in which the consequences of a mistake are high, it clearly makes sense to allow students to master component skills in safe environments before applying those skills where their correct performance is critical. What often has been in question is the cost of realism, and how this realism should be measured.

This paper describes the design and development of a simulation-based training environment where training is administered over a wide geographic range, and where cost considerations demanded effective use of an installed hardware base. The nature of the task and the stringency of the constraints forced the design team to achieve a very clear focus on training goals and resulting design criteria. The resulting product provides an information-rich environment by means of fully functional simulation to achieve highly effective training at a controlled cost.

DIMENSIONS OF FIDELITY

The most common dimension for measuring "realism" is the accuracy with which the physical environment of the job is represented. The importance of physical fidelity grew from an "identical elements" theory of transfer that is nearly a century old (Thorndike, E.L. and Woodward, R.S., 1901). Adoption of this theory caused simulation and training engineers to focus on maximizing the number of characteristics of the training environment that match those of the job environment. This approach has been used extensively in simulation for flight crew training, and has been beneficial, proving to be both practical and effective as guidance for simulator design. However, the elements which have been made identical are nearly always defined in physical terms, leading to elaborate installations and mathematical modeling which extends beyond perceptible limits.

Fidelity, or the lack of it, has been under scrutiny in the technical literature for many years. In 1980, D.R. Farrow surveyed the then-available literature in a presentation to the Society for Applied Learning Technology (SALT) conference of that year. In this paper, he noted that some writers had begun to consider the reduction of fidelity along some dimensions when high realism in irrelevant areas might actually detract from learning.

The preeminence of physical fidelity was entirely appropriate as long as psychomotor skills were the major training requirement. It is still highly appropriate, in many cases. When the desired trained behavior is to coordinate the manipulation of flight controls with cues received from visual and instrument displays - in other words, basic airplane handling skills - it makes perfect sense to strive for a simulated environment where these cues are made to resemble the cues available in actual flight. Physical stimuli elicit the onset of controlling actions, and provide data for the evaluation and modification of the action or initiation of subsequent action. Manual control of the aircraft can be seen as a continuous series of approximations and corrections in response to physical feedback from the environment. The more accurately the physical environment is simulated, the more accurate the feedback, and hence the more representative the task performance.

The training of maintenance technicians focuses on an entirely different skill set. While psychomotor skills are important, the major training requirement is cognitive. Fault isolation, or troubleshooting, is a problem-solving task, making use of highly detailed information on the state of the system being maintained. A prior paper made the point that problem-solving behavior improves as the range of information and techniques available to the technician increases through experience (Bresee and Greenlaw, 1992). Training provides synthetic experience, and the appropriate training environment increases its effectiveness.

While psychomotor training requires fidelity of physical stimuli, decision-making training requires fidelity of information. The term *cognitive fidelity* has come to be used for this dimension. Cognitive fidelity is taken to mean the realism of information content, presentation, and management options that is present in a simulated task environment. This topic was explored in a previous publication (Bresee, J. and Naber, M. 1991), where the training requirements of tactical decision making tasks were examined. Here, a decision was described as a choice to be made that is not dictated by a procedure. These relatively unconstrained choices are guided by heuristics which are formed from fundamental principles, as modified by the results of practice. For this practice to be effective, and for the resulting skills to reliably transfer to the job environment, cognitive fidelity must be high.

It has been argued that decision making, especially in team environments, is more or less effective to the extent that a common mental model of the task environment is shared by members of the team (Cannon-Bowers, Salas and Baker, 1991). This same point of view was advocated by Judith Orasanu at the International Airline Transport Association symposium on aircrew training in September of 1992. In her presentation, Orasanu advocated the building of shared mental models as the precursor for cockpit crew problem-solving tasks. She cited communication of accurate, realistic information about the problem situation as the critical element in building these shared mental models through which problem-solving heuristics were applied. Both researchers would seem to support an emphasis on high cognitive fidelity as a foundation for accurate and useful mental models.

When cognitive fidelity is maximized, it does not always follow that physical fidelity is also high. Part task trainers optimized for decision training have been successful in fulfilling their mission without high physical fidelity in every aspect of their design. This can be illustrated by examining the aspects of fidelity included in training devices which have been designed for training tactical skills. These are decision making skills, and are improved through practice in handling information of the nature and quality of that received in an operational setting. This has some similarity to maintenance troubleshooting behavior. In both cases, trainees must learn what information to select, as well as how to act upon it.

DESIGN EXAMPLE: A FUEL SYSTEM SIMULATOR FOR TROUBLESHOOTING TRAINING

The design process followed for an aircraft maintenance training system provides an example of how optimizing cognitive fidelity increases the effectiveness of decision-making training aids. In this case, the training requirement grew out of maintenance operations for an older aircraft, where the organization was losing troubleshooting expertise through retirement. Developed for the DC-8 fuel system, this trainer was designed to provide maintenance trainees with troubleshooting expertise through practice on simulated equipment. This trainer has also been put to use, providing training and job support for maintenance technicians for over a year. It is considered successful by its users, having proved its effectiveness in supporting classroom training, individualized practice, and support for actual flight line troubleshooting.

The training requirements driving the design of this device were clearly cognitive from the first. Providing accurate information in a realistic manner was accepted as a design goal from the first. However, operational constraints were also operating in that the user had a geographically wide-spread student population, and an installed base of hardware whose use was desirable. If possible, the trainer should function on a DOS-compatible computer with an 80286 CPU chip. This made it clear that extensive hardware simulation requirements would be difficult at best to implement. The discussions quickly focused on isolating the fidelity requirements which could be relaxed, and those that must remain stringent.

It soon became clear that every design consideration could be subordinated to the providing of information for the troubleshooting process. During troubleshooting, information is gathered from instruments and other data-delivering devices, but also from the physical condition of the system itself. This is also impacted by student entry level. If a component or system is unfamiliar, its physical status will not be readily perceived, and this itself becomes a training requirement. Entry level emerged as a key factor in making specific trade-offs between physical and cognitive fidelity factors.

As design discussions continued, the team was able to abstract an engineering rule-of-thumb for design with respect to physical and cognitive fidelity requirements: The importance of specific physical fidelity is reduced when components and tasks are familiar. Once the form of a control or display has been learned through repeated use, unless its exact form and function is task-critical, it is no longer cognitively relevant (salient) and need not be represented with high physical fidelity. However, when items of equipment - or displays on familiar equipment - are unfamiliar, their exact form and function are cognitively new, and physical fidelity becomes important as a component of cognitive fidelity.

The team also considered the physical requirements of the information acquisition and management tasks that comprise DC-8 fuel system troubleshooting. These tasks are performed within the cockpit environment, using the fuel panel itself. The trainer must not require the student to operate this panel differently than that of the aircraft; otherwise, false diagnostic cues may be introduced. This line of thought gave rise to another cognitive design rule of thumb: Reductions in physical fidelity cannot add distracting difficulty to task performance. For example, choosing to represent the fuel quantity gauges as a CRT graphic cannot result in providing different information about the rate of tank filling than would be shown by the actual aircraft instrument.

This rule of thumb was found to have a corollary: Limitations on physical fidelity must not result in excessively modified task performance. For example, a CRT representation of the fuel control panel cannot compress or alter the spatial relationship of components to the extent that actual diagnostic procedures cannot be authentically performed.

Here again are the four rules of thumb for cognitive design that have been discussed to this point:

1. The importance of specific physical fidelity is reduced when components and tasks are familiar.

2. When items of equipment or information displays are unfamiliar or task-critical, physical fidelity becomes important as a component of cognitive fidelity.

3. Reductions in physical fidelity cannot add distracting difficulty to task performance.

4. Limitations on physical fidelity must not result in excessively modified task performance.

These four statements relate the need - or lack of need - for physical fidelity to cognitive training requirements. Further reflection upon the nature of the troubleshooting training requirement added two more candidate design rules:

5. Cognitive fidelity is increased when all information normally available (both necessary and extraneous) during actual operations is present in the training environment.

6. Cognitive fidelity is increased when all control options and actions (both relevant and irrelevant) that are available during actual operations are present for training.

As the trainer design process continued, these rules of thumb proved increasingly valid. For example, it was quickly established that all trainees were highly familiar with the cockpit layout of the aircraft, and with the major components of the fuel system. The four principles addressing physical fidelity limitations were completely applicable. A two-dimensional graphic representation of the fuel control panel was adopted. The circuit breaker panel, of keen interest in troubleshooting tasks, was considered to be so familiar that only reports of its condition were required. The team elected to use a pop-up window showing the condition of any individual circuit breaker upon query.

Schematic-like maps were used for the large components (tanks, pumps, lines) for troubleshooting tasks. However, the customer informed the team that not all students understood the structure, function, operation and control of all pumps, valves and sensors in the system. Therefore, some preparatory modules were added where the structure and function of each class of pump. valve and sensor was graphically modeled. Here, two-dimensional representations were used as a compromise. Higher physical fidelity was desired, but not considered practical.

Frame-oriented computer-based training (CBT) is often used for improving the look and feel of aircraft maintenance training. The customer had originally considered this approach. However, the essential nature of the troubleshooting task required a significantly more realistic approach than the paginated treatment that CBT often applies to a complex process. Troubleshooting is, more than anything else, a classical problem solving task. The trainer design had to support the basic requirements for solving problems:

- Complete information regarding the problem, both relevant and irrelevant.

- Unconstrained choice of action within the domain of the problem

- Accurate and appropriate knowledge of results.

These requirements coincide completely with the fifth and sixth rules of thumb mentioned above. This forced the design team to use a system simulation. CBT developers often produce products which appear to be simulations in that trainees interact with representations of controls, and see changes in control position or system state. However, in many of these products, the student may not deviate from the desired "pathway" of control actions. These products are often called "path simulations" to distinguish them from fully modeled "freeplay" simulations. Full and complete information about any system fault does not come - in any cost effective manner - from a set of pre-programmed faults and fixed diagnostic paths. It was clear that only a fully functional system simulation providing a freeplay environment would provide the necessary cognitive fidelity for carrying out the troubleshooting task.

The resulting design was a system simulation written in C in an MS/DOS environment using an EGA graphics interface. This resulted in a readily transportable product useable on a diverse installed base of computational equipment. Moreover, this product was useful for more than only training tasks. Because this trainer incorporates a full freeplay model of the fuel system, technicians have used it as a flight line performance support system. By using the instructor mode to selectively fail system components, technicians can confirm or disprove a tentative diagnosis of an actual operational problem.

SUMMARY

This paper has offered some concrete guidelines for the use of cognitive design principles in the design of a maintenance training environment. It has described a trainer designed in this manner, whose employment as an interactive job aid as well as classroom training device shows that high training value can be attained through part task trainers with relatively low physical fidelity, provided that cognitive fidelity remains high.

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