Title
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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 10(0)

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Publication Date
1988

Peer reviewed

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1. Our coached practice environment, Sherlock, was a massive undertaking and we would like to acknowledge: Jaya Bajpayee, Marilyn Bunzo, Dennis Collins, James Collins. Richard Eastman, Drew Gitomer, Bob Glaser, Bruce Glymour, Sherrie Gott, Linda Greenberg, Debra Logan, Maria Magone, Thomas McGinnis, Sandy Stanley, Arlene Weiner, Richard Wolf, Laurie Yengo, and the officers and personnel of the 1st and 33rd Tactical Fighter Wings at Langley and Eglin Air Force Bases.

The work was done as part of subcontracts with HumRRO and the Universal Energy Systems, who were prime contractors with the Air Force Human Resources Laboratory. Many of the tools that permitted us to efficiently conduct this project were put in place by earlier efforts and foresight of the Office of Naval Research.

Instructional strategies for a coached practice environment

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Better understanding of proficency in complex real-world tasks is needed, both for assessment of skill and for training. As part of a program of research on assessing and training complex problem solving, we have developed a computer program that provides coached practice for an electronics troubleshooting job. Sherlock was developed for first-level airmen who diagnose and repair navigational equipment for the F-15 aircraft. It provides trainees with realistic fault isolation problems in a simulation of the United States Air Force's F-15 manual avionics [2] test station. Avionics units are attached to a test station via a test package that adapts the unit to the test station. The test station simulates the aircraft and how the unit would work on the aircraft and measures unit performance. However, the test station is complex and is prone to failures itself. Thus, often the trainee must troubleshoot faults in the test station before being able to diagnose and repair avionics components. Troubleshooting the test station is the most complicated aspect of the job since there is little training in this area prior to on-the-job experience, and job supports are incomplete. Sherlock was developed for first level airmen, as a supported practice environment for learning troubleshooting techniques that could be applied in the real world. There are several instructional strategies that guided Sherlock's development, each of which were driven by our empirical cognitive task analysis research in this field (Lesgold et al., 1986).

Background. We assume that our trainees are active learners. They are coached as needed while solving problems, thereby presenting opportunities to construct new knowledge that is linked to the mental state at which it will be needed. Sherlock has a **holistic procedural training** emphasis, which means that supported practice of the overall troubleshooting process is provided rather than practice of discrete knowledge skills. People learn to do complex cognitive procedures by doing them. When a trainee[3] cannot handle the whole performance, he is supported through the parts he cannot handle, via reminders and hints, but at the same time he is still enacting the whole target cognitive performance. Core mental models are not explicitly revealed but are discussed and elaborated when an individual's performance indicates that explicit help is needed in a particular part of the overall target performance. Much of our tutoring simply stimulates a technican's interrogation of the problem space rather than provide explicit guidelines on what to do next. An example of how interrogation is fostered would be the following hint delivered by our tutor to a trainee working on a problem: *"What relays in the A1A1A13 are being set by this code? How can you test this card to determine if the correct relays are set?"* If such a hint were insufficient a more explicit hint would be provided, such as, *"You should test pins 41, 42, and 46 with respect to ground (pin 51) and see if the data signals are good. "*

Sherlock presents 34 problems based on our concept of "effective problem spaces" (see Lesgold, Lajoie, Logan and Eggan, in prep.). These are subgoal lattices of plans and actions that an individual might make while troubleshooting. Both expert and novice moves are included in the representation, thereby predicting ahead of time most of the steps that a technican might make on a particular problem. At each decision point or node in the effective problem space, available hints

2. Avionics refer to electronics equipment for aircraft navigation. The F-15 is a tactical fighter plane.

3. Most, but not all, of our subjects were male. We use the masculine form only to simplify sentence structure.

focused on relevant curriculum issues as well as what the appropriate actions, test outcomes, conclusions, and next best moves would be at that point. While there was no unique best path or sequence for solving a problem, there were definite expertlike ways of troubleshooting. Proficient troubleshooters collect appropriate information to confirm or disconfirm a specific hypothesis regarding fault location. The effective problem space accommodates different levels of expertise in planning. Each subgoal node has one or more expert ways to confirm or disconfirm a particular hypothesis. Less skilled individuals are tutored in these expert moves. Usually this involves hints provided on demand, but Sherlock also may intervene to limit time wasted repeating moves or following hopeless dead ends.

Every plan or action in the problem space has as many as four types of hints, for the choices of which action to take, what outcome to expect and how to interpret it, what conclusions to draw, and what to do next. For each hint type, there are five levels of explicitness. Trainees receive these hints when they ask for help or show that they are having difficulty with particular curriculum issues. How explicit the hint is depends on how well the tutor expects the trainee to perform at that point. The performance expectations are based on a student competence model that is updated after each problem. Only a small portion of the tutor design is presented here since it has been reported elsewhere (see Lesgold, Lajoie, Bunzo & Eggan, 1988).

An Integration of Theories

Glaser (1985) and Resnick (1985) have called for an integration of several kinds of theories to guide instruction: (a) a theory of competence that describes the skilled performance that we hope to evoke in the learner; (b) a theory of acquisition that describes how people construct knowledge and gain skill; and (c) a theory of intervention that specifies how to activate the learner's acquisition processes. These three theories were considered in our tutor's design.

A Theory of Competence. The development of Sherlock was driven by a cognitive task analysis of an avionics electronics troubleshooting specialty (see Lesgold et al, 1986). We derived curriculum issues for the tutor from the cognitive competencies found to characterize troubleshooting proficency. Specifically, we had looked for differences between trainees who were acquiring their skills quickly and those who were not (based both on supervisor ratings and performance of subjects on difficult diagnosis tasks). Proficient troubleshooters were skilled at generating and testing their fault isolation plans, as well as using the appropriate methods to resolve their hypotheses. These more-skilled performers were also better at the overall troubleshooting process and at using their strategic knowledge and operational methods for solving problems. The curriculum we derived from this analysis reflects 82 aspects or components of skilled performance in three major categories: (a) procedural knowledge of basic troubleshooting procedures, such as setting up the test station correctly; (b) declarative or operational knowledge of measurement-making, such as knowing which test equipment to use and when to use it; and (c) strategic knowledge, such as serial tracing through circuit paths, space splitting, and device and system understanding.

We concluded that it is better to train specific situated competence holistically, permitting transfer to come from concepts and procedures that are common or that can be generalized from experience in multiple situations, rather than to teach abstractions that a trainee might not be able to map to various situations. Rather than teach any one curriculum issue in isolation, there were often several issues that were relevant to plans or actions in a troubleshooting problem.

Hoping to make Sherlock an expert teacher, we relied on an interesting body of research into pedagogical competence. Leinhardt (1986) examined how math teachers organize their knowledge and how they transmit this organizational structure to their students. Expert math teachers provide not only clear presentations of a new mathematical procedure but also several contexts in which it is applied. Rehearsal is provided for both the skill and understanding in many contexts so that students can see the conditions under which this new procedure applies.

In developing Sherlock we hoped to replicate this teaching expertise. **Specific domain expertise** is necessary in a tutor. For a system to be able to shape performance toward expertise, it must reflect, in its coaching, the expertise of real workers who have learned to do the job, not just the expert designer's model of the work environment or the job as represented by doctrine. Our expert, Gary Eggan, was a "worker" as well as a "teacher" who had worked in the job as an enlisted airman and later become a technical advisor to airmen doing the job. He provided us with a rationale for problem selection and with clear representations of the problem space for each problem, including likely expert and novice paths to solution. Thus several solution paths were mapped out along with coached practice for each path. Our coaching structure was developed to provide rehearsal and understanding of skills in many contexts so that individuals could see the conditions under which a new procedure applied. Rehearsal of skills is presented every time the student asks for help. The first hint he receives is a structured rehearsal of what he has done on that problem, so he can reflect on his plans and actions. Further, each time additional help is requested he gets a trace of the hints already received. Thus, the actions, outcomes, conclusions and options for a plan or action can all be reviewed during the solution process,

Understanding is fostered in many contexts. Each node can give hints about the conditions under which certain things would be true. For example, *"These data signals should cause relays K3 and K2 in the A1A1A13 card to set. One way to determine if the A1A1A13 card is operating properly is to do an ohms check on the relays being set by the stimuli code select thumbwheel switches. You could ohm out the lower contacts of K3 (between Pins 1 & 3) and the lower contacts of K2 (between Pins 55 & 57) to determine if the relays are being set."* The content of the hints are specific to the work environment, realistic and detailed.

The role of experts is essential to the development of efficent scripts and procedures for fault isolation. The history taking procedure is an efficent script for electronics troubleshooters. In history taking the technician examines what devices are active for the current test step and looks at the previous tests that have passed. Thus he builds a set of hypotheses as to where the fault might lie, and also can disconfirm hypotheses, by comparing the test step that is currently failing with steps that have passed. Hypotheses are generated by determining what in the current test differs from other tests. For instance, if a measurement device was used to measure voltage in test 1 and test 1 passed, and used again in test 2 in the exact same way but test 2 failed, one can infer that this measurement device is not the problem . However, if the type of measurement changed from one test to another, the measurement device for the second test would be a suspect device since it is a new addition to circuitry already demonstrated to be sound. This is one example of an expert procedure tutored by Sherlock.

Processes of Acquisition. Understanding the processes of acquisition is necessary for sequencing of instruction to maximize learning. We approached this by identifying the knowledge that differentiated skilled and less-skilled performers. A major finding in our cognitive task analysis research was that skilled airmen did not do better than less skilled technicans on discrete knowledge components such as basic electronics knowledge or basic operations, such as knowing where to put meter probes on a circuit board to get a particular measurement. Instead, expert troubleshooters were better primarily at orchestrating all of the cognitive competencies necessary for fault location. Our results support Estes' (1976) observation regarding performance on intelligence measures: that it is not enough to identify cognitive processes, but rather it is how these processes become organized for efficient performance that distinguishes higher levels of proficiency. Given our findings, we decided that the processes of acquiring troubleshooting skills had to be taught in the context of a troubleshooting problem so that individuals would learn how to orchestrate their skills rather than just be able to perform such skills when the cognitive load was low. We recognize that the practice of some component tasks until they become automated through practice may enable more effort to be directed to higher level tasks (Schneider, 1984; Perfetti & Lesgold, 1979). However, component processes that work well separately may not work well together. If a task demands orchestration of component skills, then assessment must be able to differentiate skill inefficiencies from skill absences. Sherlock assesses component skills in the context of assessing performance levels for individual curriculum issues. The trainee who does poorly on one skill but well on another will receive coaching based on the learned state for each particular issue. Different levels of hint specificity are provided based on the learned state for particular skills. Thus we sharpen those skills that need to be sharpened in the context of the problem space.

Understanding the knowledge a trainee brings to the learning environment makes the task of instruction simpler since instruction then consists of coherence building (Resnick, 1985) or restructuring the individual's current knowledge to a higher level of comprehension. The learning process consists of connecting new information to existing knowledge. Learning takes place on the basis of existing mental models and theories held by students, which can either enhance or retard learning (Glaser, 1985). Glaser states that with proper instruction students can test, evaluate, and modify their current theories on the basis of new information.

Sherlock reinforces prior knowledge and builds up mental models of performance through specific coaching. Both a general mental model of the troubleshooting process and a specific mental model of a test are taught. Understanding the basic troubleshooting scenario includes such things as collecting the correct resources, understanding the current test, analyzing device history, and tracing schematics. The mental model of a test, for example, consists of a stimulus input to the unit to be tested, a circuit-adjusting load, and a measurement of output. Other mental models deal with automatic configuration of equipment to carry out a test. Sherlock's coaching structure addresses these mental models in each problem. Sherlock reinforces these mental models by providing hints that teach individuals self-regulatory or metacognitive skills. Specific tutoring on device and system understanding link the student's problem solving ability to his prior knowledge.

Self-regulation is taught by providing recapitulations of the student's problem solving trace when a trainee asks for help. These hints encourage him to reflect on his decision-making process by illustrating his prior hypotheses. If a trainee does something inefficient the tutor tells him why his actions are redundant given his prior problem solving activities. Sherlock teaches the trainee to constrain the problem space and efficiently test hypotheses. When a trainee retests a unit that was already ruled out, Sherlock will say something like, *"you have already eliminated this device as a problem area by swapping the card with a good card, why don't you try something else?"*

Sherlock confronts the student to consider his hypotheses, make conclusions, and then choose alternative plans and actions based on test outcomes. It tutors device and system understanding by linking test procedures to actual problem solving performance. If, for instance,a trainee tried to perform actions that specifically were contrary to the test steps being used, then Sherlock would say something like the following, *"Testing this card is not necessary since it is not being used in this test. When you enter Measurement Code Select 12 and press Enter, you should be activating TPA12. Perhaps you should check your schematics again."*

Thus, student actions are linked to system knowledge by pointing to the information in the technical resources that highlight the relevant device knowledge. A theory of competence and an understanding of the processes of acquisition were used to develop Sherlock. Our theory of intervention links these two theories in the form of the coached practice environment. However, there are other things that a theory of intervention must consider.

Theory of Intervention. Research must test the effects of particular forms of teaching and instructional materials on particular students. Sherlock has the advantage of being able to monitor the trainee's progress through instructional materials and provide adaptive forms of instruction based on individualized performance.

Individual differences in aptitudes and learning styles play an important role in learning from instruction, and no one form of instruction fits every individual's needs (Cronbach & Snow, 1977). Some individuals are much better with spatial-visual instruction whereas others derive more meaning from verbal-textual representations. Sherlock minimizes the effects of learning differences by providing multiple medium presentations.

Just as different modes of instruction must be considered so should the focus of instruction. There is some controversy as to whether or not educational curricula should focus on general thinking skills, specific skills or both types of knowledge at the same time. Some would argue that knowledge competencies in a domain and the ability to think about that domain develop hand in hand (Bransford, Sherwood, Vye & Reiser, in press). Studying a domain requires a split focus, where one focus is on the material itself and another focus is on checking to see that the appropriate mental operations are produced to facilitate learning and problem solving (Locke, 1975; Simon, 1980).

Even though teaching both specific knowledge skills and general problem solving skills simultaneously is difficult and demanding, there is evidence that this approach to instruction has long term benefits. An excellent example can be given for teaching reading comprehension. Palinscar & Brown (1984) provided a learning environment where inquiry was encouraged and students were encouraged to be consciously aware of the strategies they used in the context of reading. Strategies were taught with procedures for where, when, and how to use them. Comprehension monitoring strategies were taught by encouraging students to check their inferences and organize their knowledge. This split focus of instruction was successful: students made significant improvements in the quality of their summaries and questions as well as overall gains on criterion tests of reading comprehension. Furthermore, these skills were demonstrated to transfer to novel tasks.

General and specific skills were tutored by Sherlock by providing opportunities for interrogation or inquiry, by teaching troubleshooting procedures and the conditions under which such procedures were useful, and finally by an emphasis on self regulation. Inquiry was supported in two ways: (a) students could ask for assistance anywhere in the problem space, and; (b) Sherlock would sometimes respond by asking questions itself.

Were the Instructional Strategies Effective? Given the instructional strategies that underlie Sherlock we can ask whether theory driven design of a coached based practice environment improves instruction. The answer in our case is yes. A pre/post test comparison of electronics troubleshooting performance of a treatment and control group was examined and the results indicated that the tutored group did significantly better than a control group on post test performance ($X2\ (1, N = 77) = 3.67$, $p < .05$, tutor group mean problems solved = 39, control group mean problems solved = 21). In addition the tutor group was shown to significantly increase their number of expert moves ($F(1,27) = 28.85$, $p < .000$, tutor group mean expert moves in post test = 19.33, control group mean = 9.06) and decrease bad moves ($F(1,27) = 7.54$, $p < .01$, tutor group mean bad moves in post test = 1.89, control group mean = 4.19). In an independent analysis, Gott (1988) found that the tutored subjects' performance rose by the equivalent of 47 months on-the-job experience as a result of the Sherlock experience. Tutoring individuals to test their hypotheses, to reflect on the results of their measurements, to understand the procedures and conditions under which such procedures work, resulted in positive performance gains. The treatment group increased their proportion of expert like tests providing evidence that tutoring a mental model of a test improved performance.

However, there were several instructional strategies used in our coached environment and we must discover which of these strategies were reponsible for Sherlock's success.

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