Effectiveness of a Computer-Coached Tutoring System for Enhancing Electrical System Troubleshooting Skills

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Abstract: Motivated by studies of how people gain technical skills, this research assessed the efficacy of a computer program for developing troubleshooting skills. Thirty-four university students enrolled in an advanced electronics course participated in the study. In addition to fulfilling the same course requirements as the control group, the experimental group used the Technical Troubleshooting Tutor to practice solving electrical fault problems. Students were encouraged to develop a problem space for each scenario, collect and interpret information, generate hypotheses and select procedures to locate faults. Following the treatment, all subjects were asked to repair faulty electrical systems during which verbal protocols were collected. The tutor group showed a dramatic improvement over the control group in their ability to troubleshoot electrical systems. No differences were found in domain-related knowledge although the tutor group demonstrated greater cognitive and metacognitive skill than the control group.

Machines in the late twentieth century are becoming increasingly complex. This creates problems for those who keep the technical systems operational. The technicians and mechanics who diagnose and repair today's increasingly complex equipment need different skills than were needed in the past. Likewise, the task of training individuals to maintain, calibrate, and troubleshoot complex systems becomes decidedly difficult. Troubleshooting is more than following a set of rote learned procedures or assembling pieces of fragmented knowledge to reconstruct understanding. Troubleshooting requires technicians to use their knowledge, skill, and experience intelligently to interact with a complex technical system that is behaving in some unusual way.

In conventional skill training programs, instructional emphasis is placed on the acquisition of theoretical knowledge and the learning of rote procedures. The overemphasis of theoretical knowledge of technical systems occurs at the expense of practical troubleshooting skill development. The tendency of instructors to emphasize theory over practice is partly due to the belief that theoretical knowledge can guide practical skills. Theory-oriented instruction is also easier to plan, manage, and deliver than activity-based training.

In contrast to the traditional approach, this study assessed a learning environment that facilitated troubleshooting practice, and at the same time, taught how to (a) develop a causal model of system functions, (b) associate thinking skills with learned knowledge, and (c) readily transfer skills to real world tasks. These ideas were implemented in a prototype computer program called the *Technical Troubleshooting Tutor*.

The tutor can be characterized as a "computer-coached practice environment" (Lajoie & Lesgold, 1989) for cognitive enhancement. The program provides a microworld environment designed around realistic computer-presented fault simulations. Problem scenarios are presented to students and they must process a set of learned knowledge and skills to identify faults by collecting and interpreting information available from the system, developing a problem space representation, and selecting test procedures to locate potential faults. During the problem solving activity, students are coached by the computer to think qualitatively and perform like an expert.

In many instructional settings, it is common for students to solve only a few problems during a course. This is due to a combination of factors. First, troubleshooting exercises take a long time to complete because of the equipment manipulations and technical tests that must be completed. Second, few school laboratories have sufficient work stations to allow an entire class to engage in troubleshooting exercises. Without sufficient numbers of work stations, instructors must be creative in their selection of activities so students remain busy during class time. As a result, considerable laboratory time is spent on tasks that are ancillary to actual troubleshooting experiences (e.g., soldering, crimping, and circuit design exercises). Because the Tutor emphasizes the cognitive activity involved in troubleshooting and de-emphasizes the time consuming physical manipulations, students have the opportunity to solve many technical problems in a short amount of time. The Tutor teaches students troubleshooting strategies by helping them represent and solve various problem situations and equips them with readily transferable skills by allowing them to work with realistic tasks.

Underlying Instructional Model and Pedagogical Principles

The primary goal of the Technical Troubleshooting Tutor is to train people to think effectively in the context of maintaining a complex electrical system. Thinking effectively while troubleshooting requires more than the use of memory or job aids to blindly follow rote learned rules or procedures; it also involves the flexible reconstruction of understanding to create new knowledge. In other words, students need to deal with related and unusual problems, be able to recognize the relevant and conflicting data, and decide what strategies to employ after collecting all necessary information related to the problem.

To achieve this goal, the instructional design of the Tutor was based on the instructional model illustrated in Figure 1. The instructional model attempts to characterize the fundamental thinking processes involved in the troubleshooting activity. As the model indicates, all instructional activities in the Tutor build on the process of problem space construction. The model is separated into two main phases; (1) problem space construction, and (2) problem diagnosis.

In the problem space construction phase, the system provides an interface that facilitates the student's acquisition of problem information in order to construct a problem space. The system also provides feedback to help the student fine tune the problem space by comparing the student's current problem space with that of an expert. At this stage, the student will use the cognitive skills of analysis, interpretation, and evaluation as problem information is considered. In the problem diagnosis phase, the system provides an environment where the student can apply different procedures to make technical evaluations of various hypotheses, reinterpret problem information, and refine the problem space. At this stage, the student will rely on the cognitive skills of evaluation, executive control, and decision-making. In addition to the instructional model, the design of the Tutor also incorporates six pedagogical principles that are believed to make the simulated troubleshooting activity be more educationally sound.

Provide a Meaningful Learning Environment

Instruction often promotes the understanding that teachers are all knowing authorities, that problems are simple and straightforward and can be solved by applying the methods or formulas just covered in class, and that there is usually only one right answer. In contrast, instruction that occurs in real world contexts promotes a different type of understanding. Real world instruction promotes an understanding that knowledge is uncertain, learning is not an orderly process, and not all problems have straightforward and simple solutions. Therefore, knowledge gained through realistic activity is more likely to transfer to new situations.

Learning within real-world contexts does not mean that instruction must take place outside the school classroom. Our instructional purpose is to train learners so they can transfer their skills to real problem situations. Providing "authentic" tasks challenge learners to collect and interpret the available symptoms, identify potential faults, and derive methods for testing those potential faults. Experiential learning can help students to realize the function of their learned knowledge and have a more vivid picture of how the learned knowledge relates to real-world tasks.

It was hypothesized that proper mental representations could be induced by providing realistic problem information. It was also hoped that the use of authentic problems would allow students to readily transfer their skills to actual tasks. Therefore, each individual learning activity designed in the Technical Troubleshooting Tutor simulates typical real-world troubleshooting tasks involved in maintaining a small aircraft's electrical system. For each scenario, learners play the role of a troubleshooter facing various customer complaints, problem symptoms, and systems with different operating conditions. The problems are complex enough that students must integrate both declarative and experiential knowledge rather than simply relying on textbook-like information to solve them. For example, one problem involves a six-year old aircraft that is parked on a runway apron at a small field. The weather has been unseasonably hot and dry. The owner of this aircraft logged two hours of flight yesterday and reports that the electrical system to failed erratically, causing him to make an emergency landing. According to previous maintenance records, routine maintenance had been performed by a qualified maintenance facility and the power supply was replaced last week by a senior mechanic at the facility. However, when the learner undertakes a routine maintenance task such as switching on the power supply, its breaker trips and he notices that nothing in the system works. As this example shows, the wealth of information that is accessible to the student is realistic and rich in both context and complexity. Another example of a realistic problem used in the Tutor is shown in Table 1.

Emphasize Qualitative Thinking and Mental Representation

Research on problem solving has illustrated that expert problem solvers usually spend proportionally more time thinking qualitatively than novices (Schoenfeld, 1985). Qualitative thinking in a troubleshooting situation includes analyzing the problem, exploring hypothetical possibilities, and evaluating progress. In contrast, novices spend more time implementing their solutions with little qualitative analysis.

Hypothesis generation and evaluation are also critical to successful troubleshooting. A previous study found that good troubleshooters tend to generate more hypotheses and better evaluate those

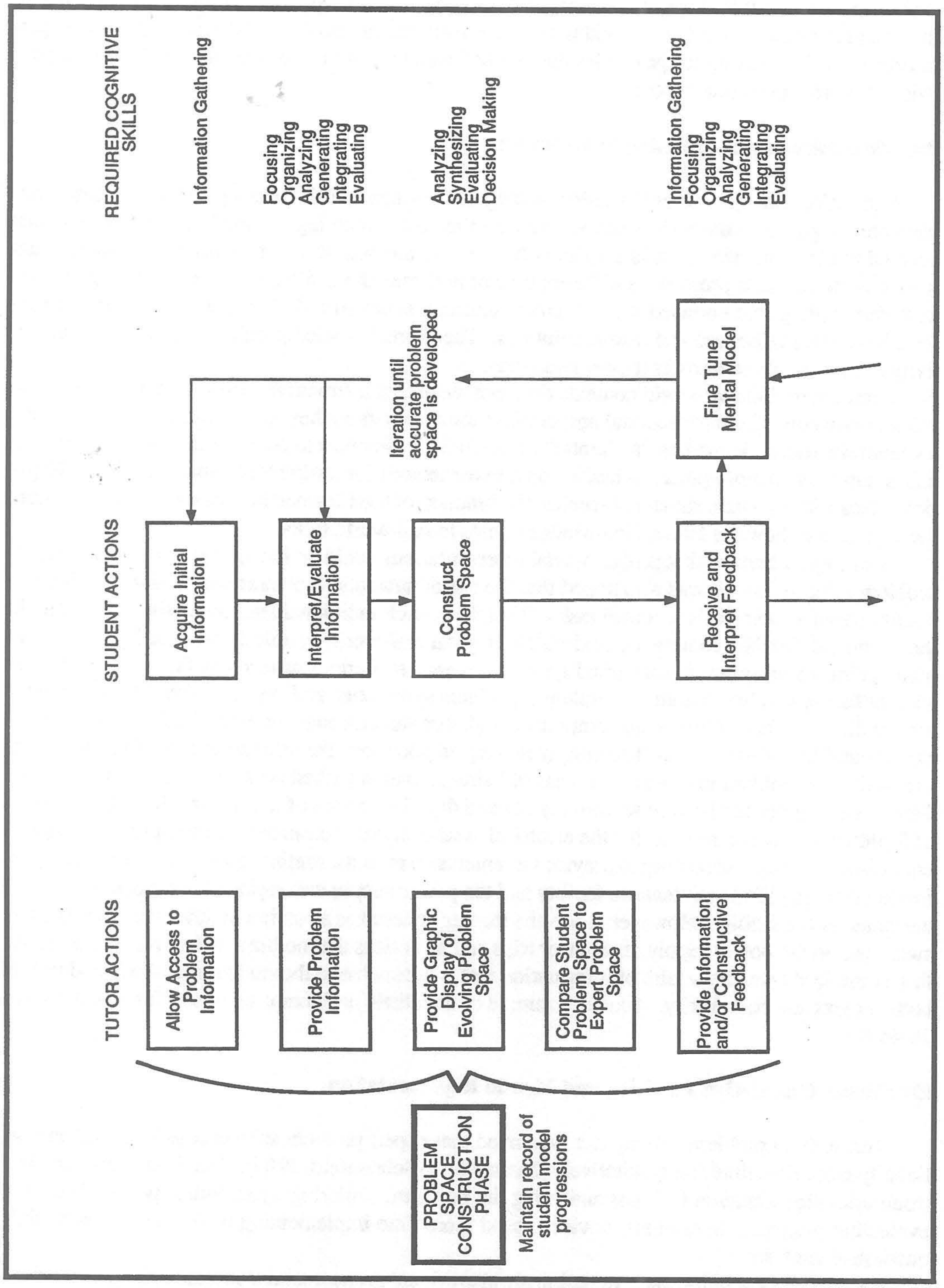

Figure 1. Problem space construction phase of instructional model

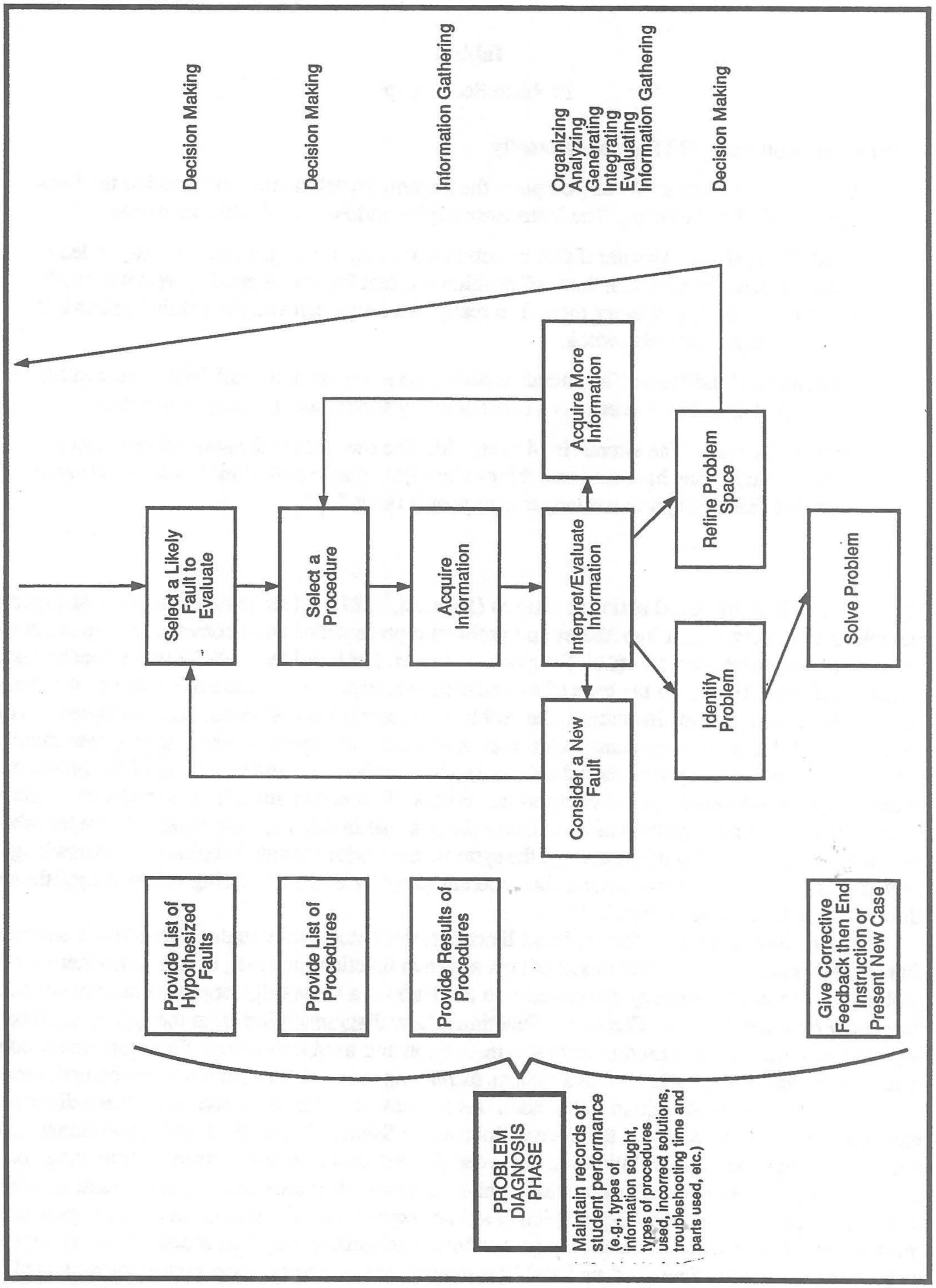

Figure 1 (continued). Problem diagnosis phase of instructional model

Table 1

Problem Set Example

Problem: Coil Relay R2 Shorted Internally

Problem Symptoms: When you place the Beacon Switch in the "on" position the Beacon Circuit Breaker trips. The Instrument Lights and Position Lights are normal.

Pilot Complaint: I wonder if that switch is worn out. I was just getting ready to leave when I placed the switch in the "on" position and that Breaker tripped. I reset it a couple of times but it tripped every time. I'm really in a hurry, can you get to this right away? I'm sure its just that old switch.

Operating Conditions: The aircraft is parked on a runway at a small field. The weather is cool and dry. The owner runs a small delivery service and passenger business.

System History: The aircraft is 14 years old. The owner says the maintenance logs are at home but he may have let some things slip a little due to cash flow problems. He also says that "all those parts last longer than people think."

hypotheses before any actual actions are taken (Johnson, 1987). Other research shows that experts are able to develop relevant hypotheses and problem representations that correspond with the deep structure of the problem context (Chi, Feltovich, & Glaser, 1981; deKleer, 1985; Larkin, McDermott, Simon, & Simon, 1980). In the case of troubleshooting, expert representations relate to the functional structure of systems. In contrast, the problem representations of novices lack an awareness of the functional structure of systems. One may speculate that experts possess appropriate mental configurations of how a system should behave and have a thorough understanding of the functional relationship between each system component. With sufficient domain-related knowledge, experts represent problems accurately in order to locate the possible faults. Novices apparently are less able to create a proper mental configuration of the system. Even with enough domain-related knowledge, they still have difficulty representing the problem properly and formulating relevant hypotheses (Johnson, Flesher, Jehng, & Ferej, 1993).

By extending ideas from the expertise literature, the Tutor assists students to derive a strategy that helps them develop a mental model of how a system functions and that, in turn, helps them solve problems. The mental strategy integrated into the Tutor is a knowledge organization tool called a *functional flow diagram* (see Figure 2). Functional flow diagrams differ from the typical engineering or schematic diagrams used in technical instruction and troubleshooting. First, functional flow diagrams present a simplistic view of a system, displaying only essential parts while schematics tend to display all components within the system. As a result, students who learn from these diagrams gain a holistic understanding of the system (Johnson & Satchwell, 1993). Second, functional flow diagrams convey the causal relationships between the system's essential parts (e.g., activating component A causes component B to activate) while schematic diagrams lack explicit causal relationships. Third, functional flow diagrams imply a time sequence within the system (i.e., component A must change before component B changes), whereas schematic diagrams represent the system at only one point in time. Finally, functional flow diagrams reinforce a critical system view by explicitly showing structural relationships between subsystems. While schematics show subsystem circuits, they are not as evident to individuals who lack an understanding of the entire system.

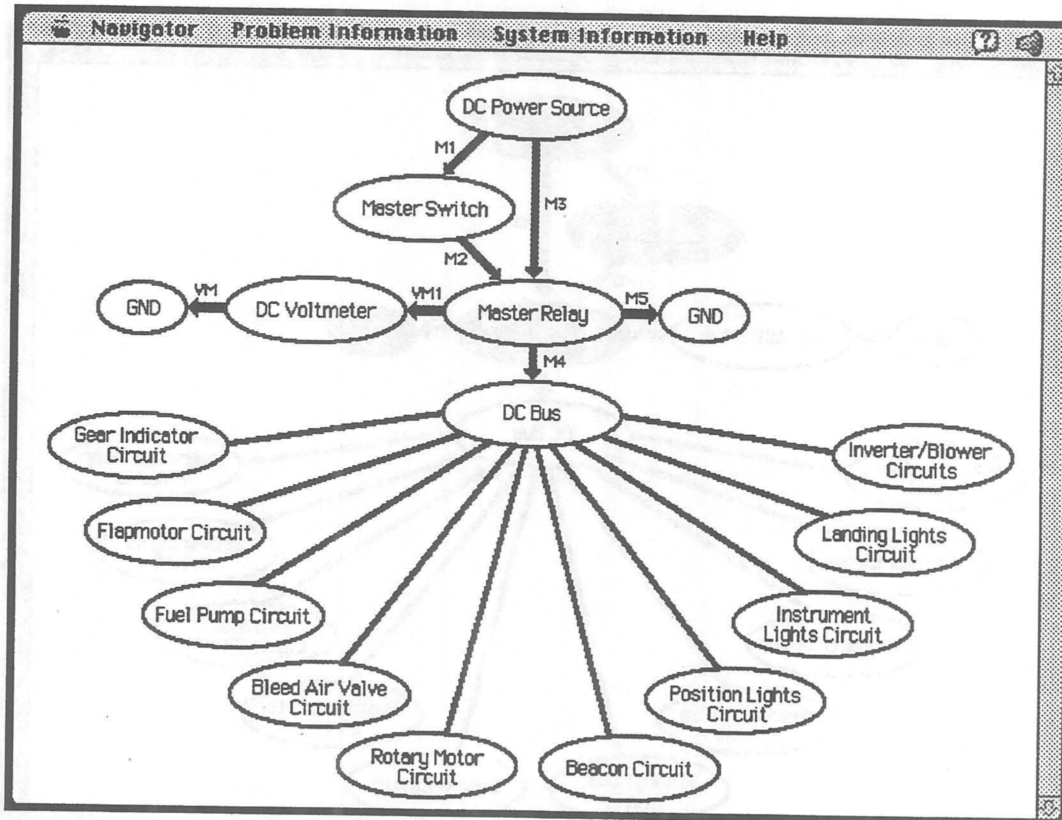

Figure 2. Functional flow diagram

Each troubleshooting task in the Tutor begins with the activity of problem representation or, more accurately, "problem space construction." The student learns to build a problem space before proceeding to actually analyze specific faults in an aircraft electrical system. The accuracy of the problem space is directly related to how well they will be able to solve the problem (Johnson, 1987). The system will penalize learners who fail an accurate problem space and instead begin blindly applying various troubleshooting procedures. Therefore, learners become motivated to spend more time making qualitative analyses (e.g., constructing a problem space, generating hypotheses, and making hypothesis evaluations) before they apply their troubleshooting procedural knowledge.

Functional flow diagrams serve as a *mental job aid* which is used to organize knowledge, create an effective problem space, and attend to the relevant information while troubleshooting a system (Novak, Gowin, & Johansen, 1983). The functional flow diagrams used in the Tutor were designed to ease the load on student's working memory and to direct their attention to the key aspects of the problem. Based on a concept called a *graphical problem space*, the Tutor uses visual cues to reinforce the development of a problem space (see Figure 3). On each problem scenario, the student uses a mouse to point to a location on the functional flow diagram where the fault *may* exist. When the student clicks the mouse button at that location, that portion of the diagram will be highlighted if it could contain the fault. As the student selects additional potential fault locations, a visual representation of the problem space is developed. If the student selects a location that could not contain the fault, the Tutor provides immediate feedback about the wrong selection. The Tutor also allows the students to query for a more elaborate explanation of why that location could not contain the fault.

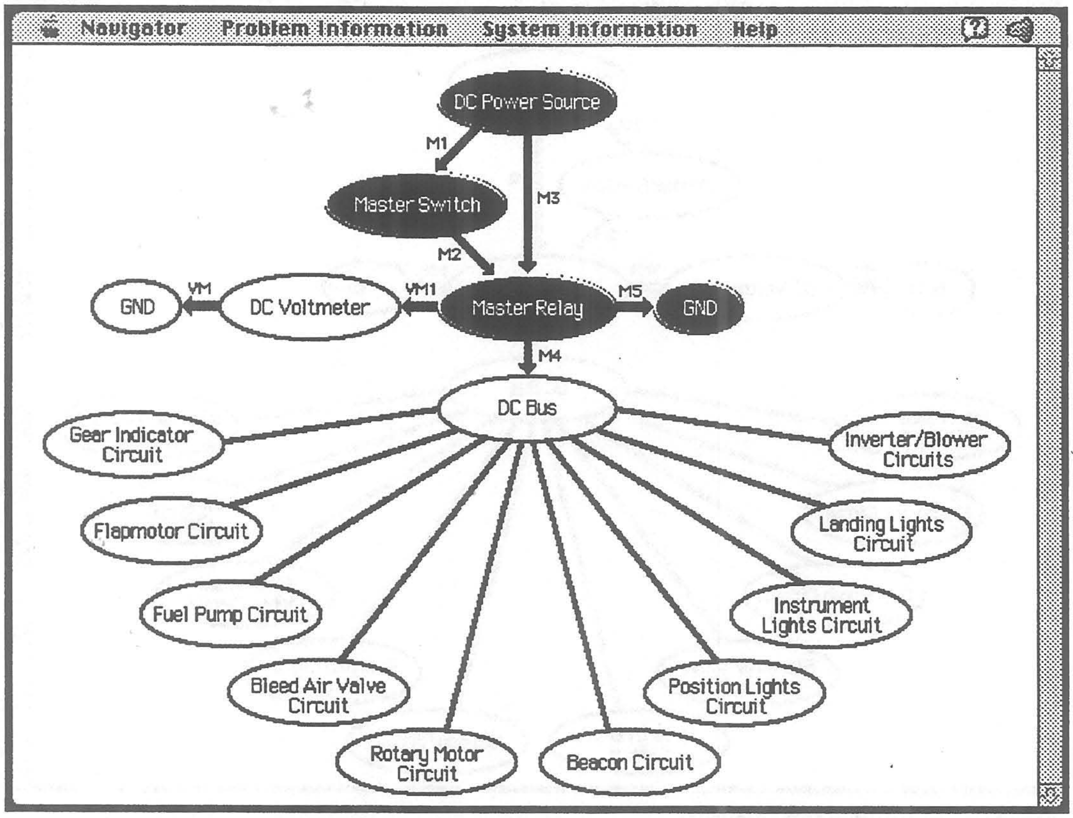

Figure 3. Graphical problem space example

Guide Learning through Reflection

The Tutor was designed to support a reflective form of learning. Each time learners identify an element of the problem space or select a procedure to check a potential fault, the system keeps track of the actions. This performance record serves as data that can be used for further analysis. While working on a troubleshooting task in the Tutor, learners can evaluate their performance by looking back on what they have done at any point. They can review their problem space and observe the effects of the different troubleshooting procedures they used. They also can use the performance record to monitor and control their troubleshooting behavior and make their troubleshooting more effective.

The Technical Troubleshooting Tutor also provides a reactive learning environment. A reactive learning environment is sensitive to the student's actions or responses and provides feedback that will extend the student's understanding of his own actions in a context of specific learning situations (Brown & Burton, 1987). It is not just interactive but responsive (see Figure 4). The feedback, provided in either textual or perceptual form, can affect a learner's conceptual understanding. By displaying and highlighting portions of a Functional Flow Diagram, the student can immediately envision the problem space and know where to engage in further diagnosis. Each time the student selects a procedure to check a potential fault, the system immediately provides feedback, including the results of the system check, the time spent on that procedure, and the cost in response to the troubleshooting action (see Figure 5). After completing a troubleshooting task, the student will

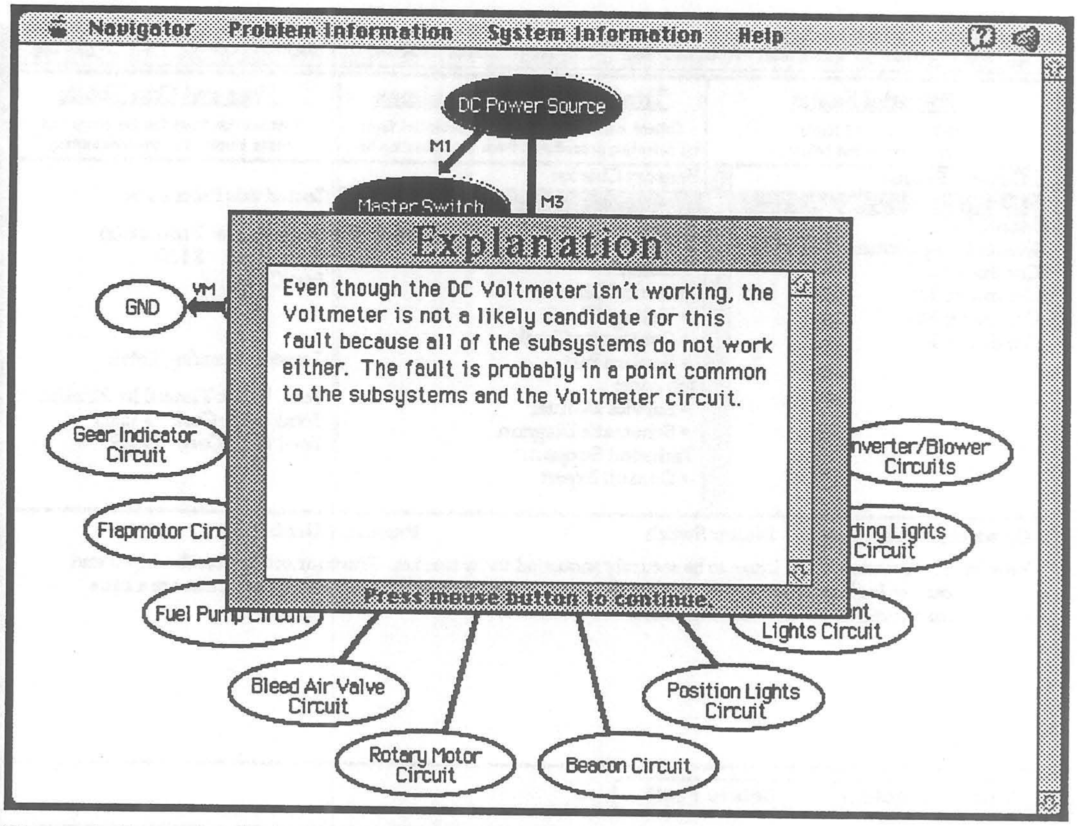

Figure 4. Example of explanatory feedback provided in the Tutor

immediately know how well the problem was solved by viewing a chart that displays a norm-based analysis on critical troubleshooting variables (see Figure 6). These response functions provide a reactive learning environment that helps learners reflect on and learn from their own problem solving behavior.

Provide a Structured Practice Environment

The Tutor also provides a structured practice environment by individualizing the selection of problems faced by students. Just as effective teachers pay close attention to each student's current level of ability and give them tasks that build on their prior learning, the Tutor sequences learning experiences based on each individual student's performance. Each time a student solves a troubleshooting problem, the Tutor will assess and summarize the student's overall performance on numerous performance indicators as compared to the norm. Based on this comparison, the Tutor makes a decision to give an easier or more difficult problem to the student for next attempt. Students must keep practicing to master a certain type of troubleshooting skill before advancing to attack another type of problem.

During the design process, content experts identified a wide range of potential faults. From that list, 56 problems were selected according to their type (i.e., shorts, opens, component failures) and level of difficulty (i.e., ranked from easy to hard). As a result, students are confronted with a broad range of challenges as they learn and practice troubleshooting skills within the Tutor.

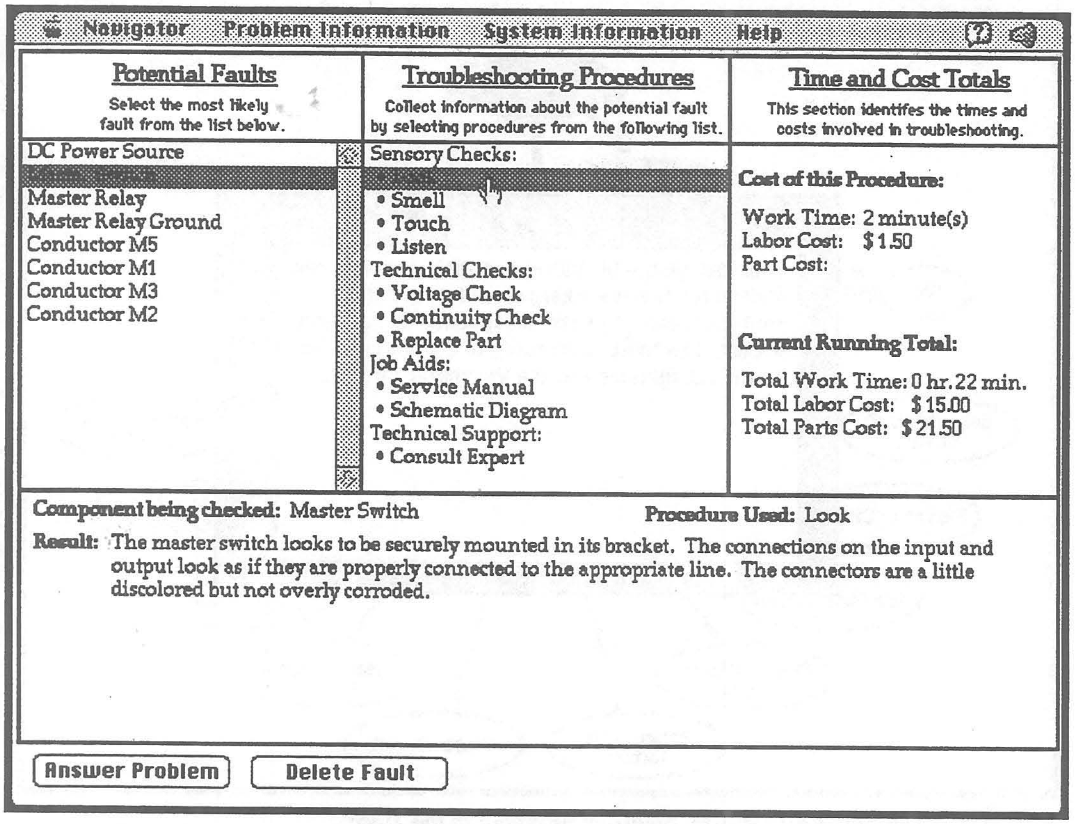

Figure 5. Troubleshooting procedure list and work time and labor costs.

Merge Constructivist and Behavioral Instruction

While the development of the Tutor applied cognitive principles, its instruction is rooted in both the constructivist and behavioral spirit. From the behavioral perspective, knowledge can be directly taught to learners and learning is seen as a process of knowledge accretion or reception. Learning activities are arranged in a manner that learners usually need to progress through a series of steps from low-level to high-level learning. Expert status is achieved through a process by which knowledge is successively acquired and organized and then integrated into existing knowledge bases.

In contrast, at the center of constructivism is the idea that learning involves individual construction of knowledge. From the constructivist perspective, learning is accomplished through a process by which learners construct an understanding or viewpoint and develop reflective awareness of that constructive process (Bednar, Cunningham, Duffy, & Perry, 1991; Perkins, 1991; Spiro, 1988). While interacting with their own environments and surrounding culture, individuals operate on the tension caused by the need to reorganize their cognitive states in order to adapt to the ever-changing environment. The potential for learning at different levels is thought to grow as the environment becomes richer and more engaging for learners.

Within the Tutor environment, the student needs to learn independently to construct and reconstruct his own problem space to locate potential faults. The student's understanding of the size and shape of a specific problem space depends on a specific problem situation. Similarly, understanding the effectiveness of various procedures depends on the feedback that is acquired after that procedure

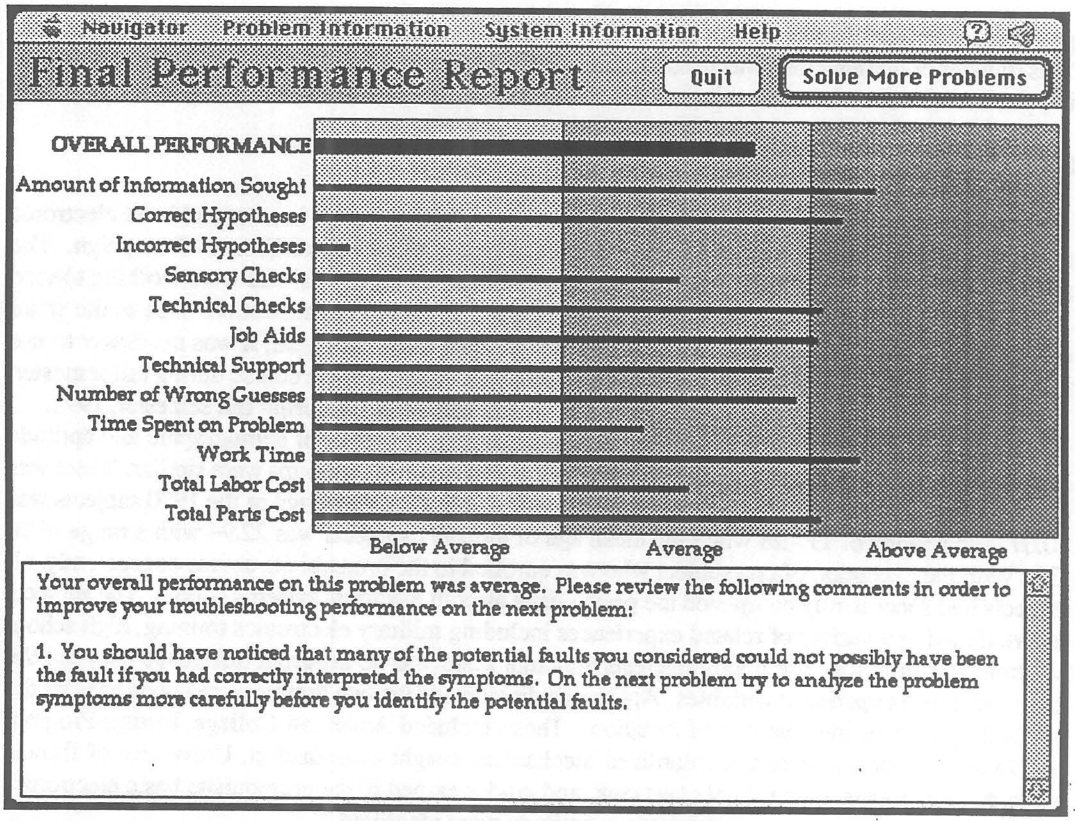

Figure 6. Performance feedback provided after solving a problem

has been applied in specific problem situations. Learning is accomplished through continuous practice of skills in various problem situations. The mixture of constructivist and behavioral principles in the design of the Tutor makes its instruction flexible and effective.

Nurture and Reward Expert Behavior

The Tutor is designed so that it promotes the selection of efficient and effective strategies to locate the fault. Rather than begin their problem-solving activity by blindly using different technical procedures to locate the fault, learners are encouraged to construct a complete problem space by collecting sufficient information before making any further decisions. Furthermore, the Tutor will give learners higher performance scores if they take appropriate procedures to check the potential faults. As research indicates, expert problem solvers tend to engage in considerable qualitative analysis before taking action. This approach forces learners to think and behave like experts; that is, they must gain a deep understanding of the problem before a solution is selected.

Method

This study examined the effect of a computer-based tutoring program on technical troubleshooting ability. Through a case-based microworld environment, subjects practiced troubleshooting by locating faults in a generic aircraft electrical system. Following the completion of the tutoring program, subjects participated in a set of laboratory problems that served as a transfer of learning task. This transfer of learning task was used to examine the impact of the Tutor on authentic troubleshooting performance.

Subjects

The target population for this study consisted of students enrolled in a second level electronic systems course at the Institute of Aviation at the University of Illinois at Urbana-Champaign. The students enrolled in this course were university sophomores and juniors who were working toward Airframe and Powerplant certification from the Federal Aviation Administration. Due to the small enrollments in this class and the fact that it is offered only once each year, it was necessary to use intact classes. The control group consisted of 16 students enrolled in the course during fall semester, 1990 while the experimental group consisted of 18 students enrolled during fall semester, 1991.

Because random selection of subjects was not possible, a variety of demographic and aptitude comparisons were made to determine if the control and experimental groups were similar. There was no significant difference in the mean ages of the two groups. The mean age of the 1990 subjects was 20.67 with a range of 19 - 28 while the mean age of the 1991 subjects was 22.94 with a range of 20 -38. With the exception of one subject who was enrolled in the prerequisite course concurrently, all subjects had successfully completed the prerequisite aircraft electrical systems course. The subjects reported having a variety of related experiences including military electronics training, high school electronics instruction, and hobby interests although there was no apparent difference between the groups on these experience variables. Aptitude indicators for the two groups were obtained from the archival records of the Institute of Aviation. These included American College Testing Program (ACT) examination scores, a standardized mechanical insight examination, University of Illinois grade point averages, high school class rank, and grades earned in the prerequisite basic electronics course. No significant group differences in aptitude were identified.

Procedure

The troubleshooting tutor was incorporated into the second level course, Aircraft Systems II, which is offered through the Institute of Aviation at the University of Illinois. This course consists of three hours of lecture and four hours of laboratory activity each week. The control group subjects completed all of the requirements of the existing course and then participated in several troubleshooting performance tasks. In addition to completing the customary course work and examinations, the tutor group subjects participated in the troubleshooting tutor treatment. This treatment involved working on the Tutor to practice solving aircraft electrical system faults. Two Macintosh IIsi computers containing the troubleshooting tutor software were placed in a computer laboratory adjoining the Maintenance Technology Department's library. The students were able to work on the tutor anytime during the day between 8:00 AM and 5:00 PM. Prior to the start of the treatment, a one hour demonstration and explanation of the Tutor was provided for the tutor group subjects. A graduate research assistant served as a supervisor whenever students were working on the Tutor. The supervisor's role was to answer questions related to the operation of the Tutor but not to provide any assistance related to the solution of problems on the Tutor.

After completing the tutor exercises each student participated in the same troubleshooting performance tasks used with the control group. The troubleshooting performance task allowed for comparisons of the effect of the Tutor on troubleshooting ability. To maximize the instructional effects of the course, the troubleshooting transfer task was conducted in the last four weeks of a sixteen week semester. Near the end of the semester, each student was individually presented with a simulator board that contained an aircraft electrical system in which four independent faults were inserted. Students were given common troubleshooting tools and were asked to locate the faults. Verbal protocols were collected and analyzed to identify the cognitive processes used during troubleshooting. Treatment effects were examined by comparing performance on the transfer task. The relationship between aptitude, domain knowledge, and task performance was also examined. In the last week of instruction all subjects completed a domain specific examination which also included a demographic questionnaire.

Transfer Measures

The apparatus used to determine post-treatment performance was an instructor-developed training board that represented ten discrete subsystems found in a small aircraft's electrical system. Aircraft components such as circuit breakers, switches, relays, terminal strips, conductors, and other major functional system components (e.g., rotating beacon, power inverter, blower motor, fuel pump, various lights, control motors, valves) were mounted on a tabletop board.

The selection of the performance tasks was based on specific criteria to ensure representation of certain populations of tasks. Technical problems can be categorized as structural, functional, and behavioral faults (deKleer & Brown, 1983). Structural problems are the result of architectural faults including inappropriate or nonexistent connections. Functional problems are those that occur when a system component fails completely, rendering it without function. Behavioral problems occur in system components that present symptoms out of the normal operating range, or as a result of interaction between marginal components.

Task selection was limited to problems that were not likely to result in immediate solution based on experience or cursory observation. Each problem was inserted so that it could be individually identified. In an effort to prevent instructor bias, the transfer task problems were not revealed to the course instructor. Expert validation of the selected faults was accomplished through a review by senior electronic service technicians in the Department of Electrical and Computer Engineering at the University of Illinois.

Data Collection and Analysis

Three data types were obtained to determine the effect of the treatment; (a) domain-referenced test scores, (b) verbal protocols from the troubleshooting performance task, and (c) descriptive data based on observations, surveys, and archival records. The domain-referenced test was designed to assess subjects' knowledge of the structural, functional, and behavioral aspects of the system represented in the performance task. A total of twenty-one multiple choice questions and three schematic-referenced items included thirteen functional items, eight structural items, and three behavioral items. All test items were evaluated by experts in the Department of Electrical and Computer Engineering at the University of Illinois. The test was administered in the last week of each semester.

Verbal protocols were collected during the troubleshooting performance task and analyzed to determine general troubleshooting performance such as problem recognition and solution accuracy. The recorded verbalizations were coded in accordance with methods established by Johnson (1988; 1989). A second rater coded approximately 20% of the protocols to validate the coding process. The two rater codings were compared for consistency with a resultant agreement coefficient above .90. Surveys, observations, and archival records were used to collect ancillary data to assess troubleshooting performance and to determine how the students felt about their interaction with the troubleshooting tutor. A reaction questionnaire was also administered after each student completed a few problems on the tutor during their first session.

relied on one strategy type and were effectively "strategy bound." Only one tutor group member used the inefficient continuity strategy for a brief time on one problem. There were no cases within the tutor group of a single strategic approach.

General Discussion

Students who worked on the Technical Troubleshooting Tutor became more effective and efficient troubleshooters than students who did not have the same opportunity. With an average of only five hours on the computer, the tutor group showed a 78% improvement in actual troubleshooting success over the control group. In comparison to the control group, the tutor group appeared more determined to locate the faults and displayed greater confidence in their troubleshooting ability. The tutor group also displayed a higher level of competence in troubleshooting strategy selection. While differences were found in performance, no statistical differences were found between the two groups in domain knowledge. These results suggest that the Tutor improved students' cognitive and metacognitive processes but not their declarative knowledge base.

The findings from this study suggest that technical instruction not only needs to equip students with sufficient domain-related knowledge but also needs to teach students domain- related skills and strategies (Bransford, Sherwood, Vye, & Rieser, 1986). The belief that theoretical knowledge is required for competent performance has been challenged by this study. This study showed little relationship between theoretical knowledge and troubleshooting performance. Students who worked with the functional flow diagrams appeared to create appropriate mental models and select efficient procedures while performing troubleshooting tasks. The functional flow diagram not only guided students to create effective problem spaces, they also helped them establish relevant hypotheses. It is suggested that students who experience well-designed strategy training will know how and when to use their knowledge appropriately while facing problem situations. Strategic knowledge needs to be explicitly taught.

This study shows that providing considerable opportunities to practice solving real problems enhances performance. Recent commentaries have indicated that knowledge is fundamentally "situated" within the activity, context, and culture in which it is developed (Brown, Collins, & Duguid, 1988). That is, the context of a learning situation will influence how the acquired knowledge will be applied in real situations in the future. The Technical Troubleshooting Tutor provided students with the opportunity to process information in a problem-oriented format so they could relate symptoms to a set of potential faults. Careful selection and arrangement of problems that are "authentic" for students will help them realize the function of their knowledge and also help them envision the possible use of their knowledge for solving real problems. Contextualizing student knowledge in authentic tasks will help them readily transfer their knowledge to actual troubleshooting tasks.

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