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ABSTRACT

A study found that the troubleshooting abilities of a treatment group of college students trained conventionally in a course called Aircraft Systems II and on a computer-based "Technical Troubleshooting Tutor" were better in some ways than those of a control group who trained conventionally without using the computer-based tutor. Aviation students at the University of Illinois participated in the study, 16 in the control group and 18 in the treatment group. Each student was given an aircraft simulator board in which four independent electrical faults were inserted, common troubleshooting tools, and the task of locating the faults. No significant differences were found in the ability of the two groups to recognize that faults existed. However, the treatment group was significantly better at actually locating and identifying the faults. The control group solved fewer than half the attempted problems, whereas the treatment group solved 72 percent. The two groups' performances on a posttest about electrical systems and their ability to identify potential faults were not significantly different. However, the treatment group was significantly better able to evaluate the faults correctly, was more likely to evaluate the systems before selecting a troubleshooting strategy, was not dependent upon a single strategy to facilitate the process, tended to make fewer misinterpretation errors, and had a stronger ability to recover from errors. (Contains 49 references.) (CML)

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National Center for Research in
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PREFACE

This report is part of the National Center for Research in Vocational Education's (NCRVE) continuing effort to improve vocational and technical curriculum and instruction. This study is one in a series of investigations being conducted by researchers at the NCRVE that examine how people learn technical information and how that information can best be taught. This particular study describes the development and testing of an intelligent computer program that coaches students as they troubleshoot simulated aircraft electrical system faults. It is hoped that this developmental study will be of interest to researchers, practitioners, and policymakers in vocational and technical education who are interested in improving the quality and effectiveness of technical training in private industry, community colleges, and vocational schools.

EXECUTIVE SUMMARY

Technological advances create problems for those involved in keeping technical systems operational. To be successful with the new technologies, maintenance technicians must have a good understanding of technological systems and possess transferable skills that enable them to access new information as technologies change. Because of the advances in technology, the most valuable job skill of the future may be the ability to think.

An effective educational training program for preparing troubleshooters is one that provides the knowledge needed to understand the technology, teaches the skills of troubleshooting, and provides students with the opportunity to practice using their knowledge and skills to diagnose faulty equipment. In the past, trainers have tended to overemphasize the theoretical concepts of technical systems at the expense of troubleshooting skill development. The tendency of instructors to emphasize theory before practice is partly due to the effect of prior instruction; that is, "we teach as we were taught." Theory-oriented instruction is also easier to plan, manage, and deliver than truly effective activity-based training. Instructors who desire to increase their instructional emphasis on experiential learning are often hampered by the lack of equipment for training purposes, limited availability of tooling, problems with wear and tear inherent in the process of assembly and disassembly, and the increased time necessary to physically do all of the activities essential for practical training.

Fortunately, instructional technologies are capable of supporting technical instruction. Intelligent tutoring systems are one form of instructional technology that utilize advanced computer technologies to coach a student through a learning experience. These systems offer instructors the flexibility to conduct practical training with more efficiency because they are no longer constrained by limited equipment and laboratory time. Learners can experience realistic troubleshooting during laboratory sessions and on their own time. As a result, more hands-on experiences can be provided in a shorter amount of time than is possible through traditional laboratory practice.

A tutoring system called the *Technical Troubleshooting Tutor* has recently been developed which simulates troubleshooting scenarios so students can practice troubleshooting aircraft electrical systems. The purpose of this study was to assess the effectiveness of the *Technical Troubleshooting Tutor* for developing troubleshooting skills in technicians.

Tutor Description

The *Technical Troubleshooting Tutor* is a form of intelligent tutoring system that can be characterized as a computer-coached practice environment. Several pedagogical principles identified in the cognitive science literature have been incorporated into the Tutor. These principles include incorporating components of apprenticeship such as coaching, fading, and scaffolding; providing a motivating microworld environment; utilizing real problems, situations, and contexts; maximizing the time spent on cognitive activity; reducing cognitive overload during practice; and nurturing and rewarding expert behavior. The Tutor provides a structured practice environment for students that is designed around realistic computer-displayed fault simulations. Students are presented with problem scenarios that they attempt to solve by collecting and interpreting information, developing a problem space, and selecting procedures to collect information in order to test potential faults. During the problem-solving activity, students are coached by the computer to think and perform like an expert.

Method

The target population for this study consisted of sophomores and juniors enrolled in the Institute of Aviation at the University of Illinois at Urbana-Champaign for the purpose of obtaining Airframe and Powerplant certification from the Federal Aviation Administration. The *Technical Troubleshooting Tutor* was incorporated into the second-level course, Aircraft Systems II. The control group consisted of sixteen students enrolled in the course during Fall semester, 1990, while the experimental group consisted of eighteen students enrolled during Fall semester, 1991.

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 coursework 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. After completing the Tutor exercises, each student participated in the same troubleshooting performance tasks used with the control subjects.

The troubleshooting performance task allowed for comparisons of the effect of the Tutor on troubleshooting ability. Each student was individually presented with an aircraft electrical system simulator board 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.

Treatment Characteristics

The tutor subjects averaged five hours and fifteen minutes on the computer Tutor during which they solved an average of thirty problems. The computer problems took an average of 10.4 minutes to solve while real laboratory problems were estimated to take more than twenty-eight minutes to solve. Based on these estimates, the computer allowed for a time savings of nine hours and fourteen minutes per student which is a sixty-three percent time savings for simulated versus real problems. As a result, the computer allowed the subjects to complete many more problems in the same amount of time than they could have completed in a traditional laboratory. In addition, the Tutor allowed the students to gain considerable experience in proper use of the cognitive strategies needed for competent troubleshooting because it emphasized cognitive skills and de-emphasized physical skills.

Troubleshooting Performance Differences

Near the end of each semester, all students individually participated in a performance task that required them to troubleshoot a faulty aircraft electrical system in which four independent faults had been inserted. There were numerous interesting differences between the two groups on their ability to complete these real troubleshooting tasks.

Ability to Recognize that Faults Exist

There was no significant difference in the ability of the control and tutor groups to recognize that faults existed in the electrical system. Overall, the control group was able to recognize ninety-one percent of the faults while the tutor group recognized eighty-nine percent of the faults.

Ability to Locate Faults

The most reliable indicator of troubleshooting performance is the realistic demonstration of that skill. In spite of the fact that both groups of subjects were equally able to recognize that faults existed within the aircraft electrical system, there was a highly significant difference in their ability to actually locate and identify the faults. The control group subjects solved an average of 1.63 problems while the tutor group subjects solved an average of 2.89 problems—a seventy-eight percent improvement in troubleshooting success over the non-tutor group. As a group, the control subjects solved less than half of the attempted problems while the tutor group subjects solved seventy-two percent of the problems.

Electrical Domain Knowledge Differences

Due to the fact that the tutor group outperformed the control group on the troubleshooting performance task, one might suspect that the treatment group had learned more about the characteristics of electrical circuits and their components. This, however, was not the case. There was no difference in the mean scores on the domain-referenced electrical system posttest examination for the tutor and control groups. Although the Tutor seems to enhance the troubleshooting ability of its users, it does not appear to increase their declarative knowledge of electrical system structure, function, and behavior. This finding is consistent with the results of other studies that have examined the relationship between domain knowledge and performance.

Cognitive Processing Differences

Research suggests that experts evaluate problems qualitatively prior to taking action. Typically this involves careful examination of the symptoms in order to predict the potential fault. During problem solving, experts constantly monitor their actions to determine whether their predictions about the problem were correct. This monitoring process allows the expert to review and change strategies until the problem is solved. The process of thinking about one's thinking is referred to as metacognition.

In this study, several metacognitive operations were used by both the control and tutor subjects. Of particular interest in this troubleshooting study are the subjects' metacognitive abilities to (1) predict the cause of the problem before taking action, (2) select appropriate troubleshooting strategies; and (3) monitor feedback for errors and self-correction.

Hypothesis Selection and Evaluation

The subjects' protocols were examined to identify the number of hypotheses they generated. Hypothesis generation is a major phase of the Technical Troubleshooting Model and serves as a goal-setting process to guide the troubleshooter in the selection of potential faults. Hypothesis statements were those comments made by the subjects that suggested a potential cause of the problem. There was no significant difference in the ability of the two groups to generate plausible hypotheses. While there was no difference in their ability to identify potential faults, there were significant differences in their ability to correctly evaluate the faults. The tutor group was significantly better able to correctly evaluate their hypotheses than the control group. As one would expect, the tutor group was also less likely to incorrectly evaluate their hypotheses. Although not statistically significant, the control group was more likely than the tutor group to make no decision about the correctness of a hypothesis. These results suggest that the experience on the Tutor enhanced the students' abilities to correctly evaluate the potential faults they considered.

Troubleshooting Strategy Selection

The type of troubleshooting strategy used certainly contributes to successful performance. An important difference was evident in the strategies used between the control and tutor groups. Tutor group members were more likely to thoroughly evaluate the symptoms before selecting a troubleshooting strategy, they used more powerful voltage checks than the control subjects, and they were not dependent upon a single strategy to facilitate the troubleshooting process.

Monitoring Errors and Self-Correction

An important aspect of the troubleshooting process is whether the troubleshooter realizes that an error has occurred and that self-correction is possible. This metacognitive operation was used to compare the types of errors committed by the two groups. Significant errors committed by the subjects included redundant checks, senseless checks made out of the problem space, and misinterpretations of acquired information. While the number of redundant and senseless checks made were similar for both groups, the tutor group tended to make fewer misinterpretation errors than the control group. The tutor group subjects also exhibited a stronger ability to recover from their errors than the control group.

Student Perceptions of the Tutor

In addition to the collection of comparative performance data, observations of the students as they interacted with the Tutor were conducted to obtain formative evaluation data. Interviews were also conducted with the tutor group students after they had completed the Tutor. Because it was in its development stage, this formative evaluation was crucial for future improvement of the Tutor.

Overall, the students stated that they enjoyed working with the Tutor and said they would most definitely recommend it to others. The students stated that they liked the graphics, the user-friendliness of the program, and the fact that everything they needed for troubleshooting was in front of them on the screen. The majority of the students found the problems on the Tutor to be challenging, and they felt that it had made them better troubleshooters. The students also indicated that the Tutor had improved their perception of the electrical systems course. Some of the students reported that their prior experience in the prerequisite electrical course was disappointing and they, therefore, expected to have a similar experience in the present course. However, they found that the opportunity to solve a large number of simulated problems on the Tutor made them feel more positive toward the domain of electricity.

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INTRODUCTION

Technological advances create problems for those involved in keeping 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. Mechanics who like to work with their hands and need to see how a device works in order to understand it are having difficulty maintaining sophisticated equipment. These "hands-on" oriented individuals can no longer rely on their perceptual and physical abilities to help them solve technical problems. The changes in technology have reduced the extent to which information that is critical for detecting faults can be obtained through direct perception. As a result, the increasing use of electronics, small scale miniaturization, and the great complexity of today's equipment has led to an increase in the importance of abstract thinking abilities. These new technologies require mental skill above physical skill and are highly knowledge intensive. Successful maintenance technicians in the future will be those who develop troubleshooting skills that involve general as well as specific understanding of technological systems. They will be those who develop the transferable skills that enable them to access new information as technologies change. Because of the advances in technology, the most valuable job skill of the future may be the ability to think.

While troubleshooting is becoming an increasingly important job skill, the development of good troubleshooters is a very difficult task. Troubleshooting is more than following a set of procedures in a service manual or practicing tasks over and over until they are perfected. Troubleshooting requires technicians to use their knowledge, skill, and experience to effectively interact with a complex technical system that is behaving in some unusual way. While some individuals seem to have a knack for developing troubleshooting skills, current research suggests that troubleshooting skills can be developed through properly designed instruction. For example, studies have identified the critical knowledge base for successful troubleshooting (Keller, 1985; Kuipers & Kassirer, 1984; Morris & Rouse, 1986), troubleshooting strategies used by expert troubleshooters (Johnson, 1989; Rasmussen & Jensen, 1974), and recommended techniques for improving troubleshooting training (Gott, 1988; Kieras & Bovair, 1984; Lesgold et al., 1988; Morris & Rouse, 1986; White & Frederiksen, 1987).

An effective training program for preparing troubleshooters is one that provides the knowledge needed to understand the technology, teaches the skills of troubleshooting, and provides students with the opportunity to practice using their knowledge and skills to diagnose faulty equipment. In the past, technical trainers have tended to overemphasize the theoretical concepts of technical systems at the expense of troubleshooting skill development. The tendency of instructors to emphasize theory before practice is partly due to the effect of prior instruction; that is, "we teach as we were taught." Traditional theory-oriented instruction is also easier to plan, manage, and deliver than the more effective activity-based training. Instructors who desire to increase their instructional effectiveness through experiential learning activities are often hampered by the lack of equipment for training purposes, limited availability of tooling, problems with wear and tear inherent in the process of assembly and disassembly, and the increased time necessary to physically do all of the activities essential for practical training.

Fortunately, instructional technologies are capable of supporting technical instruction. Although computers have been used extensively in educational settings, most applications have been confined to drill and practice while little effort has been directed to the support of higher level thinking skills. Computers can have a tremendous impact on the learning process when integrated with high quality instructional software. When the power of instructional technologies is combined with our increased understanding of troubleshooting expertise, more effective technical instruction can be developed.

Intelligent tutoring systems (ITS) are one form of instructional technology that have great potential for improving technical instruction. These systems are very powerful computer-based instruction programs that use advanced computer technologies to incorporate an expert's domain knowledge to tutor or coach a student through a learning experience. ITS offer instructors the flexibility to conduct practical training with more efficiency because they reduce the constraints of limited equipment and laboratory time. With well designed software, learners can experience realistic troubleshooting during scheduled laboratory sessions and on their own time. As a result, more hands on experience can be provided in a shorter amount of time than is possible through traditional laboratory practice.

A tutoring system called the *Technical Troubleshooting Tutor* has recently been developed which simulates troubleshooting scenarios so students can practice troubleshooting faulty aircraft electrical systems. The purpose of this study was to assess the efficacy of the Tutor for developing troubleshooting skills in maintenance technicians.

The following research questions were developed to assess the impact of the *Technical Troubleshooting Tutor* on troubleshooting ability:

1. Does the computer-based Tutor improve student's ability to solve authentic electrical system faults?
2. Is there a posttreatment difference between the Tutor and non-tutor groups' declarative knowledge of electrical systems?
3. Is there a posttreatment difference between the Tutor and non-tutor groups' use of metacognitive skills while troubleshooting?

This study also examined the students' perceptions of the usefulness and effectiveness of the Tutor for the purpose of providing formative evaluation data.

TUTOR DESCRIPTION

The *Technical Troubleshooting Tutor* was originally designed to serve as a research tool rather than an instructional apparatus. When instructional strategy research is conducted in authentic classroom settings, however, concerns arise about the influence of the instructor on the success or failure of the strategy. The success of a strategy may be more attributable to the quality of the instructor than the strategy itself. To reduce the influence of instructor quality in this study, the Tutor was designed to control the delivery of instruction so that all students would receive the same quality of instruction. This design allowed the assessment of instructional design effects without instructor quality interaction.

The *Technical Troubleshooting Tutor* can be characterized as a computer-coached practice environment for cognitive enhancement (Lajoie & Lesgoid, 1989). As a cognitive enhancer, the tutor is designed to help students who possess a set of prerequisite domain knowledge and skills. The program provides a microworld practice environment designed around realistic computer-generated fault simulations. Students are presented with problem scenarios that they attempt to solve by collecting and interpreting information, developing a problem space, and selecting procedures to collect information in order to test potential faults. During the problem-solving activity, students are coached by the computer to think and perform like an expert.

In traditional instructional settings, it is common for students to solve only a limited number of technical problems in a semester. 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 done. Second, few school laboratories have sufficient work stations to allow an entire class to engage in troubleshooting exercises at one time. 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 time-consuming physical manipulations, students are provided with the opportunity to solve many technical problems in a short amount of time. In addition, by simply adding a computer or two to a laboratory environment, additional work stations are provided. As a result of these improvements, extensive structured practice opportunities can be provided for students which help them quickly develop the same mental patterns that are developed by expert problem solvers through many years of troubleshooting experience (Nichols, Pokorny, Jones, Gott, & Alley, 1989).

Pedagogical Principles of the Tutor

The *Technical Troubleshooting Tutor* was designed around the Technical Troubleshooting Model and graphical problem space concept developed at the Training and Development Research Center at the University of Minnesota (Johnson, 1987). Several pedagogical principles identified in the cognitive science literature have been incorporated into the Tutor. These principles include incorporating components of cognitive apprenticeship such as coaching, fading, and scaffolding; providing a motivating microworld environment; utilizing real problems, situations, and contexts; maximizing the time spent on cognitive activity; reducing cognitive overload during practice; and nurturing and rewarding expert behavior.

Incorporate the Cognitive Apprenticeship Model of Instruction

Through the years, vocational and technical instructors have utilized various forms of apprenticeship in their instruction. Traditional apprenticeship typically involves an expert who models the desired quality of performance for novices, coaches them through a task, and gives them more autonomy as their skills develop. In a traditional craft guild, for example, the master models expert behavior by demonstrating to the apprentice how to do a task while explaining what is being done and why it is done that way. By observing the master perform, the apprentice learns the correct actions and procedures and then attempts to copy them on a similar task. The master then coaches the apprentice through the task by providing hints and corrective feedback as needed. As the apprentice becomes more skilled, the master gives the apprentice more control over the task by "fading" into the background.

Coach Students Through Difficult Situations

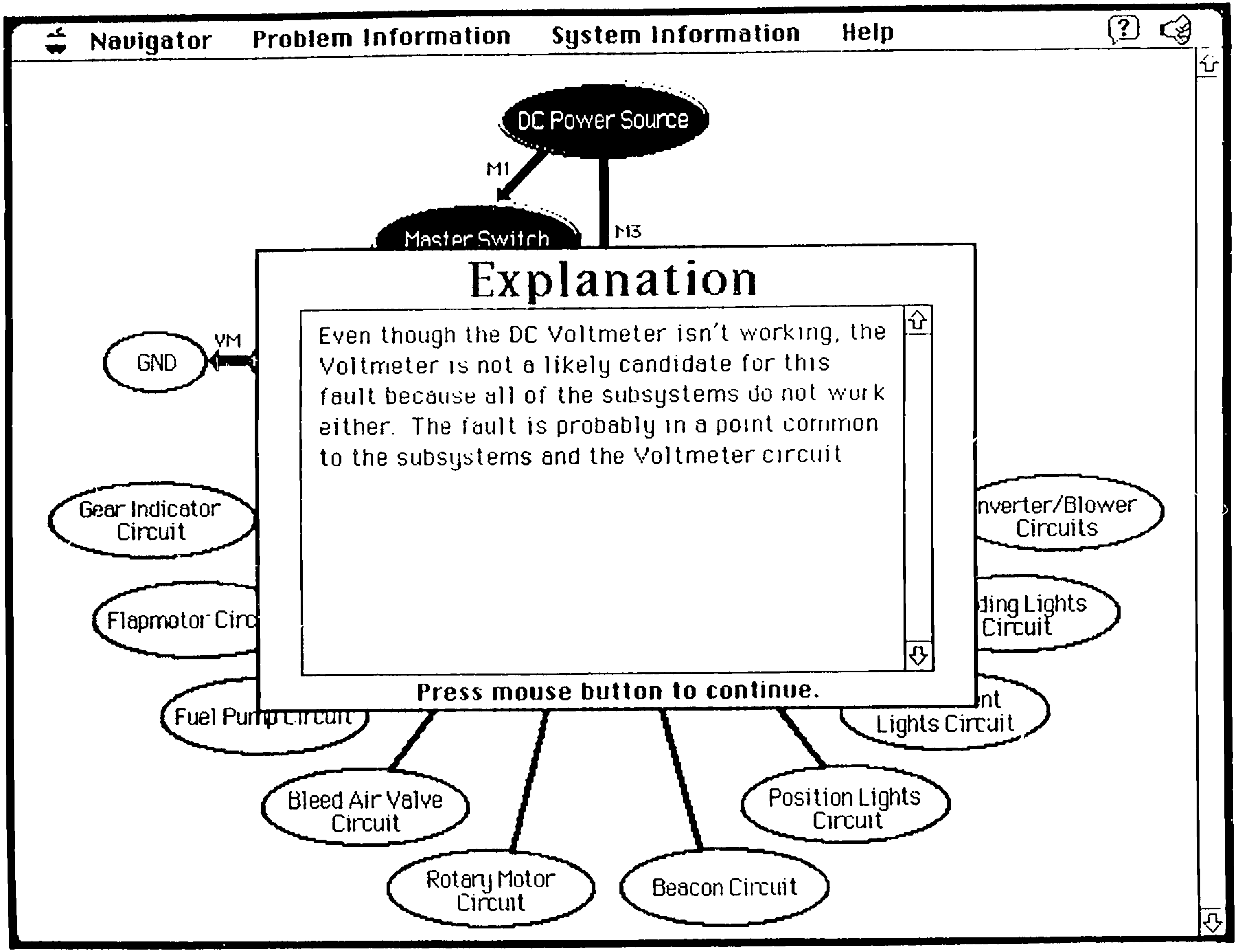
While traditional apprenticeship emphasizes physical ability, a modification of this approach called *cognitive apprenticeship* has been adapted for the Tutor to enhance student cognitive abilities. The Tutor records student actions during troubleshooting, analyzes their performance, and provides hints and assistance (see Figure 1 for an example of a coaching explanation). Proper techniques for collecting information, representing the problem space, and selecting and performing technical tests are nurtured by the Tutor through explicit support and guidance when they are most needed.

Sequence Learning Experiences Based on Individual Performance

The effectiveness of cognitive apprenticeship can be further enhanced by individualizing the selection of the 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 individual student performance. After each problem is solved by the student, the Tutor assesses the student's performance by compiling the data collected on twenty-five troubleshooting performance indicators and makes norm-referenced comparisons to other students' performances. Based on this comparison, the Tutor makes a decision to give the student an easier or more difficult problem to attempt next. The Tutor also determines if the student has successfully reached a criterion level of performance on each problem type (i.e., component failure, open circuit, short circuit). For example, if a student has successfully solved five "open circuit" problems at a high level of performance, the Tutor will present the student with problems that involve "short circuits."

Figure 1

Example of an Elaborate Explanation Provided to Coach Student Through Problem



Explanation

Even though the DC Voltmeter isn't working, the Voltmeter is not a likely candidate for this fault because all of the subsystems do not work either. The fault is probably in a point common to the subsystems and the Voltmeter circuit

Press mouse button to continue.

Fade into the Background as Student Ability Improves

As students' thinking processes develop, they are able to perform with little instructor intervention. This fading aspect of cognitive apprenticeship results in the gradual transfer of responsibility for learning from teacher to student. As students progress through the Tutor's problem type and difficulty hierarchy, they are provided with less problem-specific information and reduced levels of coaching. This fading aspect of instruction forces students to rely more on their own knowledge and skills and less on their interactions with the Tutor.

Help Students Develop Automaticity Through Practice

One of the key characteristics of expertise is an apparent ease of performance. Experts are able to perform quickly, fluently, and efficiently. There is general agreement that practice is essential for the development of skilled performance. Research indicates that practice leads to an increase in the speed of task completion and a decrease in error rate (Phye, 1986).

Practice usually involves repetition of a task or skill. Cognitive science researchers have identified the following conditions needed for practice to bring about speed and accuracy improvements: (1) knowledge of results, (2) causal attribution, (3) generation of alternatives, (4) hindsight, and (5) learning from instruction (Langley & Simon, 1981).

During practice, students must receive feedback about the results of their actions before they can improve. Knowledge of results allows students to monitor their problem-solving performance by providing information about the correctness of their performance, the length of time each problem took to solve, and the types and number of errors they made.

Through practice, students begin to see relationships between actions, conditions, and outcomes. For example, students in an electronics course may learn that closing a switch will cause a relay to energize only if a power source is available. The students may also learn that if the power source is weak or if the switch is faulty, the relay will not be energized. This awareness of causal attribution enables students to generate alternative solutions to problems. Using the above example, a student who recognizes the causal relationships between the switch, power source, and relay can identify alternative fault possibilities for a problem in which the relay will not energize. The student who does not understand the causal relationship between the three components will have greater difficulty developing plausible solutions to a problem.

Hindsight, the fourth condition of effective practice, involves the examination and evaluation of past performance based on knowledge of results and causal attribution (Phye, 1986). Through practice, students build a repertoire of successes and failures. By using hindsight to examine past performances, students can recognize patterns in their successes and failures. They can begin to recognize their own mistakes and the misconceptions that caused the errors. In this way, hindsight can improve future performance.

All four of these conditions are necessary to bring about increased speed, decreased errors, and automaticity of skill. Using the Tutor to provide opportunities for practice should facilitate and augment learning by providing feedback, developing causal understanding, emphasizing the generation of potential faults, and encouraging the use of hindsight to examine performance.

Provide a Motivating Microworld Environment

Intrinsic motivation is an essential factor in learning (Bruner, 1962). When learning activities are intrinsically motivating to students, they may spend more time on the activity, put more effort into learning, feel better about what they have learned, and be more likely to use their new knowledge and skill in the future (Malone, 1981). Based on a series of interviews with highly motivated people, Csikszentmihalyi (1978) identified the following features of intrinsically motivating activities:

1. The level of challenge for students increases or decreases based on their current level of skill.
2. Important instructional activities are isolated from other events or activities which may interfere.
3. There is a criteria for performance that clearly informs the student of his or her current progress toward the criterion.
4. Concrete feedback is provided to the student.
5. The student is confronted with a broad range of challenges.

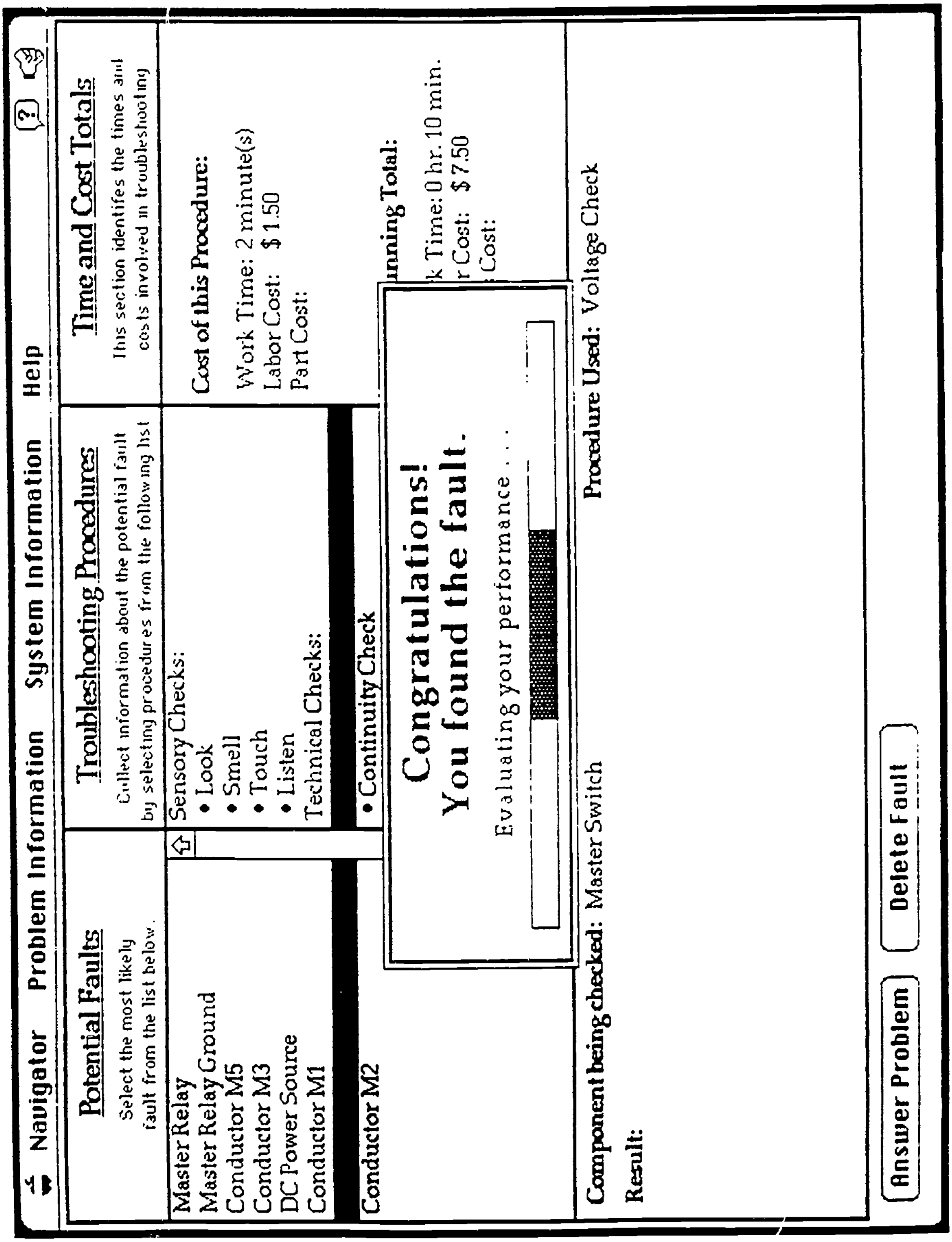
The Tutor was designed to promote intrinsic motivation through the incorporation of Csikszentmihalyi's features of intrinsically motivating activities. For example, upon completion of each problem, the Tutor evaluates the student's performance and chooses the next problem based on that performance (see Figure 2). Students are also given considerable feedback while solving the problems; comparisons of their performance to that of other students are made; and a very broad range of problem types covering an entire aircraft electrical system have been built into the Tutor.

Intrinsic motivation can also be enhanced through activities that embody fantasy and curiosity (Malone, 1981). The Tutor encourages fantasy and curiosity by simulating real activity on the computer. Examples of the variety of the problem scenarios that promote fantasy and curiosity include an aircraft that has been confiscated from drug smugglers, problems that occurred while student pilots were using the aircraft, the salvage operation of a wrecked aircraft, and troubleshooting problems encountered during a competition between aviation students from two universities.

As students work on each troubleshooting scenario, they need to perform a variety of checks which cost money and time. Using time and labor figures derived from actual aircraft maintenance settings, the Tutor records the time and cost required for each procedure used by students and provides them with an updated record of their overall cost and time performance (see Figure 3). The student's goal is to keep the simulated costs as low as possible and the simulated work time as short as possible.

Figure 2

Evaluating Student Troubleshooting Performance



Potential Faults

Select the most likely fault from the list below.

- Master Relay
- Master Relay Ground
- Conductor M5
- Conductor M3
- DC Power Source
- Conductor M1
- Conductor M2

Troubleshooting Procedures

Collect information about the potential fault by selecting procedures from the following list

Sensory Checks:
- Look
- Smell
- Touch
- Listen

Technical Checks:
- Continuity Check

Time and Cost Totals

This section identifies the times and costs involved in troubleshooting

Cost of this Procedure:

Work Time: 2 minute(s)
Labor Cost: $1.50
Part Cost:

nning Total:

k Time: 0 hr. 10 min.
r Cost: $7.50
:Cost:

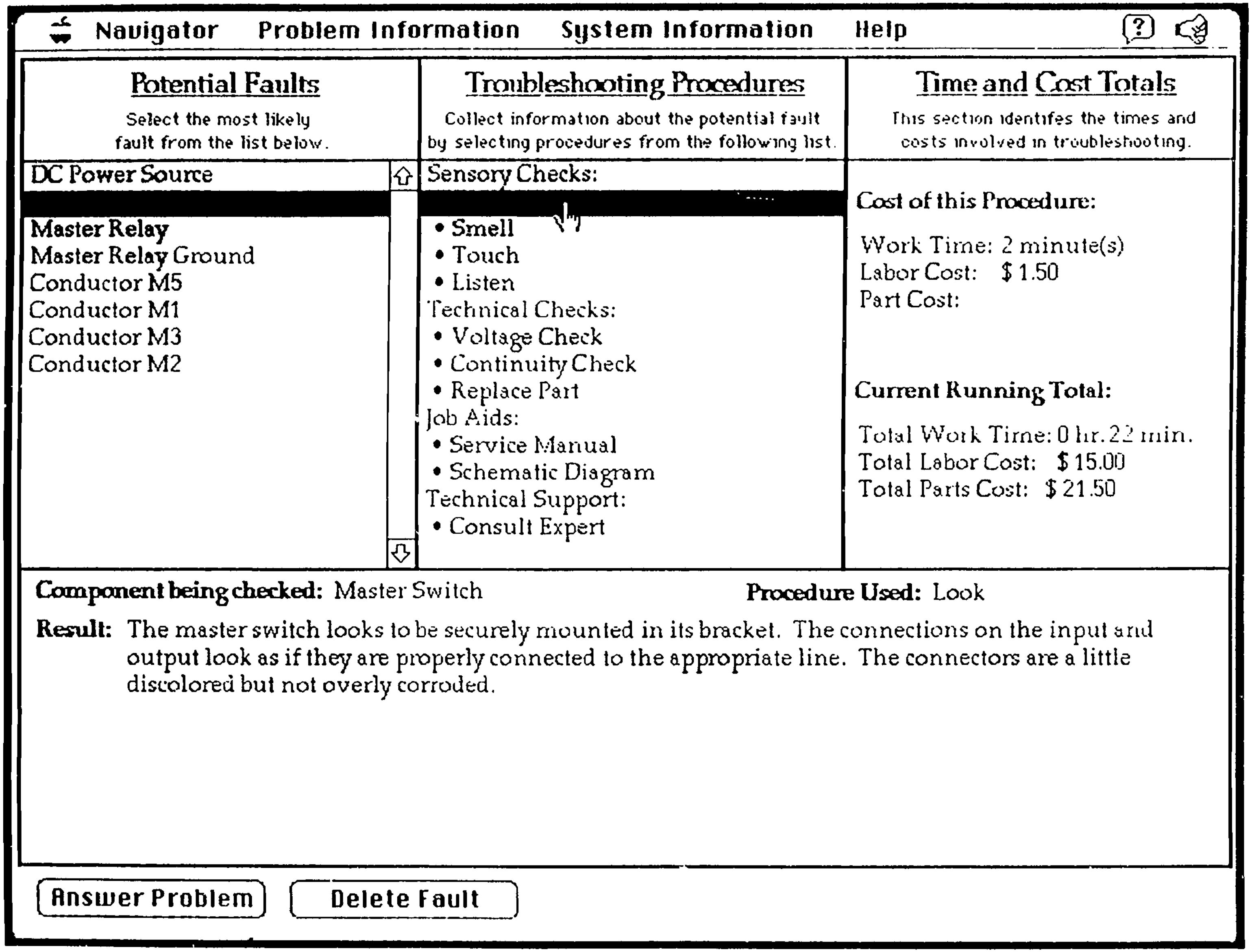
Congratulations!
You found the fault.

Evaluating your performance . . .

Component being checked: Master Switch
Procedure Used: Voltage Check
Result:

Figure 3

Running Total of Work Time and Labor Costs for this Problem



Potential Faults

Select the most likely fault from the list below.

DC Power Source

Master Relay
Master Relay Ground
Conductor M5
Conductor M1
Conductor M3
Conductor M2

Troubleshooting Procedures

Collect information about the potential fault by selecting procedures from the following list.

Sensory Checks:
- **Smell**
- Touch
- Listen

Technical Checks:
- Voltage Check
- Continuity Check
- Replace Part

Job Aids:
- Service Manual
- Schematic Diagram

Technical Support:
- Consult Expert

Time and Cost Totals

This section identifes the times and costs involved in troubleshooting.

Cost of this Procedure:

Work Time: 2 minute(s)
Labor Cost: $1.50
Part Cost:

Current Running Total:

Total Work Time: 0 hr. 22 min.
Total Labor Cost: $15.00
Total Parts Cost: $21.50

Component being checked: Master Switch **Procedure Used:** Look

Result: The master switch looks to be securely mounted in its bracket. The connections on the input and output look as if they are properly connected to the appropriate line. The connectors are a little discolored but not overly corroded.

Utilize Real Problems, Situations, and Contexts

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

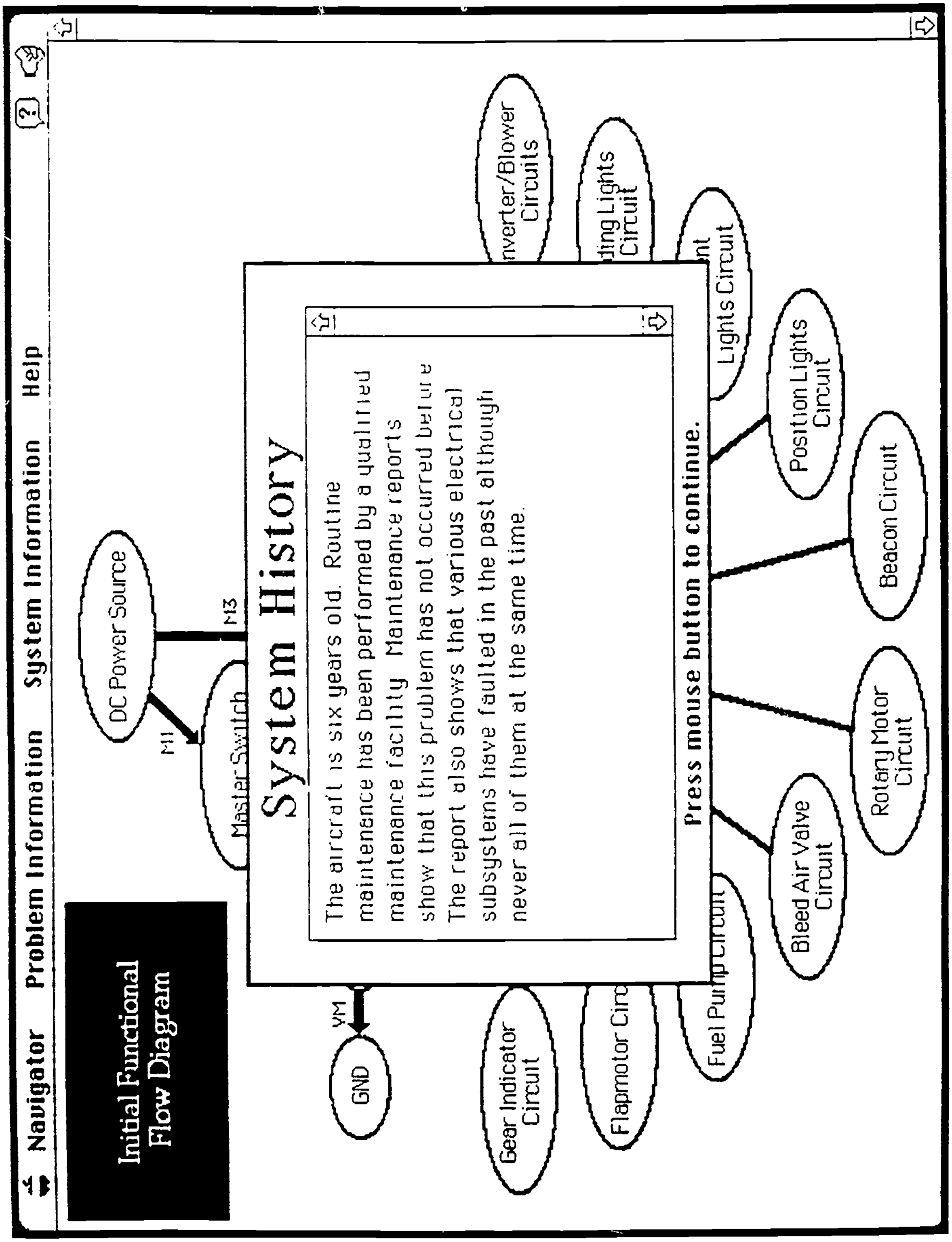
Cognitive research indicates that people learn because of the contextual information in the problem situation. *Situated learning* is a term that describes the acquisition of knowledge and skills in an instructional context that reflects the way the knowledge and skills will be used in real life (Brown, Collins, & Duguid, 1988). This concept is not new to education. Dewey (1956) urged basing education in reality and suggested that each day a student should bring home from school something which could be used that day.

Research has consistently indicated that the way something is learned influences later use of that knowledge. It appears that knowledge is indexed when it is learned so that it can be found and retrieved when needed at a later time (Glass, Holyoak, & Santa, 1979; Phye, 1986; Reiser, 1986). Several researchers have pointed out the importance of context for indexing knowledge to be stored in memory. For example, problem-oriented instruction too often takes place in contexts that are dissimilar from those the student will encounter later. Providing the opportunity for students to process information in a problem-oriented format appears to help them acquire *conditionalized knowledge*—knowledge that includes information about the conditions and constraints of its use (Anderson, 1983; Bereiter, 1984; Glaser, 1984). Students who learn under such conditions will be more likely to spontaneously use their new knowledge when necessary. Consequently, careful selection and planning of the instructional context is of prime importance in instructional design.

Learning within real world contexts does not mean that instruction must take place outside the school classroom to be effective. The Tutor was designed to use problems, situations, and contexts that the students would face as technicians in the aircraft maintenance industry. These experiential learning activities present students with real world problems and challenge them to collect and interpret the available symptoms, develop a set of potential faults, and derive methods for testing those potential faults. Figure 4 provides one example of the realistic problem information used in the Tutor.

Figure 4

Example of Realistic Problem Information



System History

The aircraft is six years old. Routine maintenance has been performed by a qualified maintenance facility. Maintenance reports show that this problem has not occurred before. The report also shows that various electrical subsystems have faulted in the past although never all of them at the same time.

Press mouse button to continue.

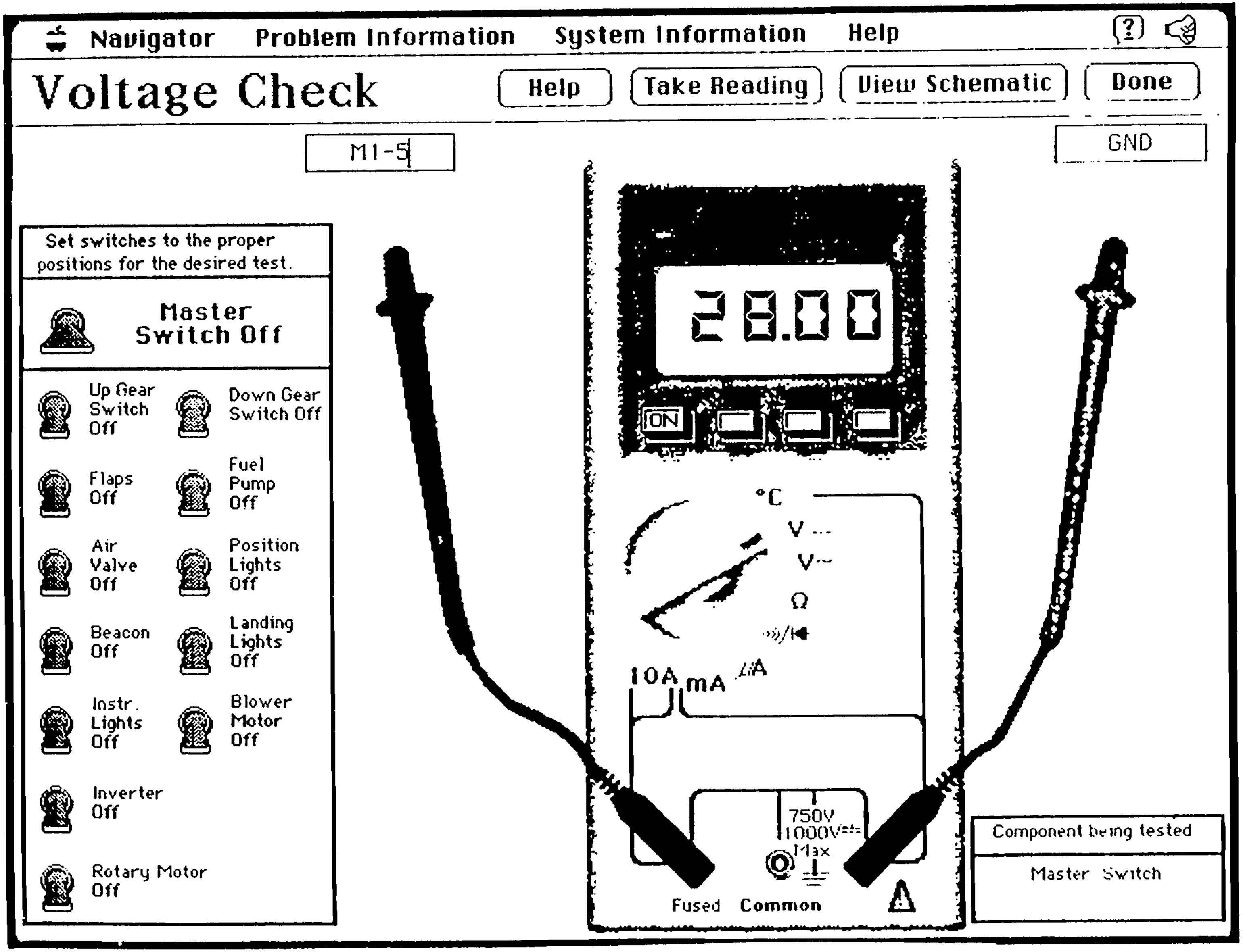
Maximize the Time Spent on Cognitive Activity

One of the keys to the development of expertise is having extensive opportunities to practice using cognitive skills (Phye, 1986). The cognitive skills needed for troubleshooting include skills such as acquiring and interpreting information, identifying attributes and components, recognizing patterns, and generating and evaluating hypotheses. In most technical courses, however, instruction takes the form of teacher-directed lectures and physical skill development activities in a laboratory (Johnson, 1990). Students tend to be passive receptors of information during lectures and often spend their laboratory time replicating activities that have already been performed by the instructor. For example, students will often use laboratory time to complete non-troubleshooting related tasks such as soldering, crimping various types of wire connectors, splicing wires, and developing basic hand tool proficiency. As a result, the amount of time students actually spend on cognitive activity is very limited.

Building on the current capabilities of computer technology, high fidelity troubleshooting scenarios have been designed into the Tutor (see Figure 5 for an example of the digital meter that is simulated in the Tutor). Real troubleshooting tends to take a long time due to the physical actions needed to collect information run tests, and make repairs. Because students do not have to physically remove panels and loosen bolts, they can solve many problems on the computer faster than they could on real equipment. It is expected that reducing the time required to solve each problem will allow students to solve many problems and, therefore, gain more relevant troubleshooting experience in a shorter amount of time.

Figure 5

Digital Meter as Simulated by the Computer



Set switches to the proper positions for the desired test.

Master Switch Off

Up Gear Switch Off

Down Gear Switch Off

Flaps Off

Fuel Pump Off

Air Valve Off

Position Lights Off

Beacon Off

Landing Lights Off

Instr. Lights Off

Blower Motor Off

Inverter Off

Rotary Motor Off

M1-5

GND

Component being tested

Master Switch

35

34

Providing troubleshooting experience on the computer also improves laboratory management for instructors and provides individualized instruction for students. Technical instructors are often hampered by the lack of equipment for training purposes, limited availability of tooling, and problems of wear and tear on the training equipment due to the constant assembly and disassembly activities. These limitations can result in only a few students actually doing troubleshooting while the rest of a class completes non-essential, "busy work" activities in the lab. With troubleshooting training software available on computers, instructors can increase the number of work stations in a laboratory to keep a greater percentage of the class "on-task." This results in an increase in the amount of direct instruction received by each student. By having more students actually engaged in troubleshooting activity, the amount of time spent on cognitive activity is increased.

Reduce Cognitive Overload During Practice

Research shows that experts are able to process a large amount of information when solving problems while novices often get "mentally bogged down." Instruction needs to help students reduce the overload on their working memory in order to enhance their ability to learn and solve problems. One way to reduce the load on working memory is through the use of an external memory. External memories can be as simple as a list of things to do or as complicated as a diagram of an electronic device. An external memory reduces working memory load in the following three ways: (1) It contains information that does not need to be retained in memory; (2) it allows manipulation of information outside of working memory; and (3) it provides a visual, perceptual, and accessible record of a sequence or process that otherwise would need to be kept in working memory. External memory also enables problem solvers to keep track of where they are in the process of solving a problem, thereby easing the load on working memory (Larkin, 1988).

Several forms of external memories have been designed into the Tutor to help reduce cognitive overload during the troubleshooting process. These include the use of concept maps, the availability of troubleshooting performance records, and focusing attention through the development of a *graphical problem space*.

Concept Maps

Concept maps are a form of external memory aid that help students organize new information. Concept maps were originally developed as a tool for researchers to help them learn how people organize knowledge (Novak, Gowin, & Johansen, 1983). They are now being used as instructional tools to help learners process information for learning and to evaluate student learning. Concept maps help students distinguish important concepts, arrange concepts in some meaningful order, and establish significant relationships between concepts. The ability of concept maps to organize information makes it easier for students to form "chunks" of concepts that can be stored in memory.

The concept maps that have been integrated into the Tutor are called *functional flow diagrams* and are designed to help students organize their understanding of the aircraft electrical system (see Figure 6). Functional flow diagrams differ from the schematic diagrams that are commonly used for technical instruction and troubleshooting. The following list identifies the major differences between functional flow diagrams and schematic diagrams:

1. Functional flow diagrams present a simplistic view of the system, displaying only the system's *essential* component parts, while schematic diagrams display all component parts within the system. As a result, students who learn from concept maps will initially gain an understanding of the "big picture" without all the detail.

2. Functional flow diagrams can convey causal relationships between the system's essential component parts (e.g., activating component A causes component B to activate), while schematic diagrams do not explicitly convey causal relationships.

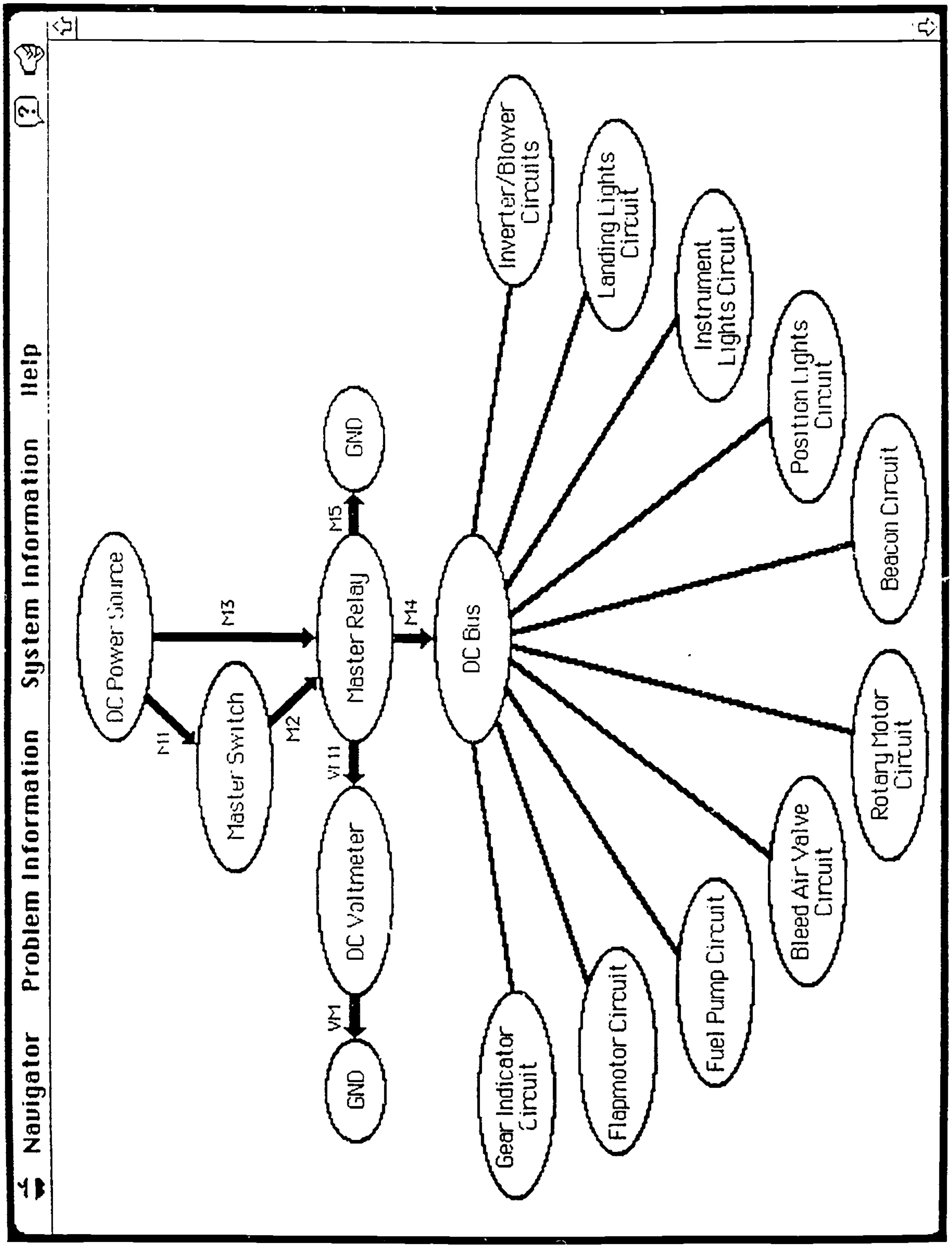
3. Functional flow diagrams imply a time sequence within the system (i.e., component A must change before component B changes), while schematic diagrams represent the system at only one point in time.

4. The functional flow diagrams can explicitly display the motion of flow through the system by the use of arrows and action-oriented concept labels, while schematic diagrams typically display the system in a stationary or static state.

5. Functional flow diagrams reinforce a critical systems view by explicitly showing common systems and subsystems. While schematic diagrams show subsystem circuits, they are not readily evident to individuals who lack a general understanding of the entire system (Johnson & Satchwell, 1992).

Figure 6

Functional Flow Diagram of a Small Aircraft's Electrical System



The Tutor also provides an external memory for students by keeping records of student performance for a wide variety of performance indicators (see Figure 7). Many of the performance indicators are available to the student for review during the troubleshooting process. For example, the student is able to look at a list of the potential faults that were considered, the types of information that were acquired, and the technical tests that were run. Having this information available from the computer allows the troubleshooter to free up working memory and concentrate on only the most important information cues.

When working on complex problems, many troubleshooters selectively reduce the size of the problem space by eliminating potential faults through the use of various technical tests (Johnson, 1988). This reduction in problem space size serves to decrease the amount of information that must be attended to in working memory. The Tutor also allows students to reduce the size of the problem space as they attempt solutions. Students are able to delete potential faults from a master list and are shown a visual representation of the reduced problem space on a concept map.

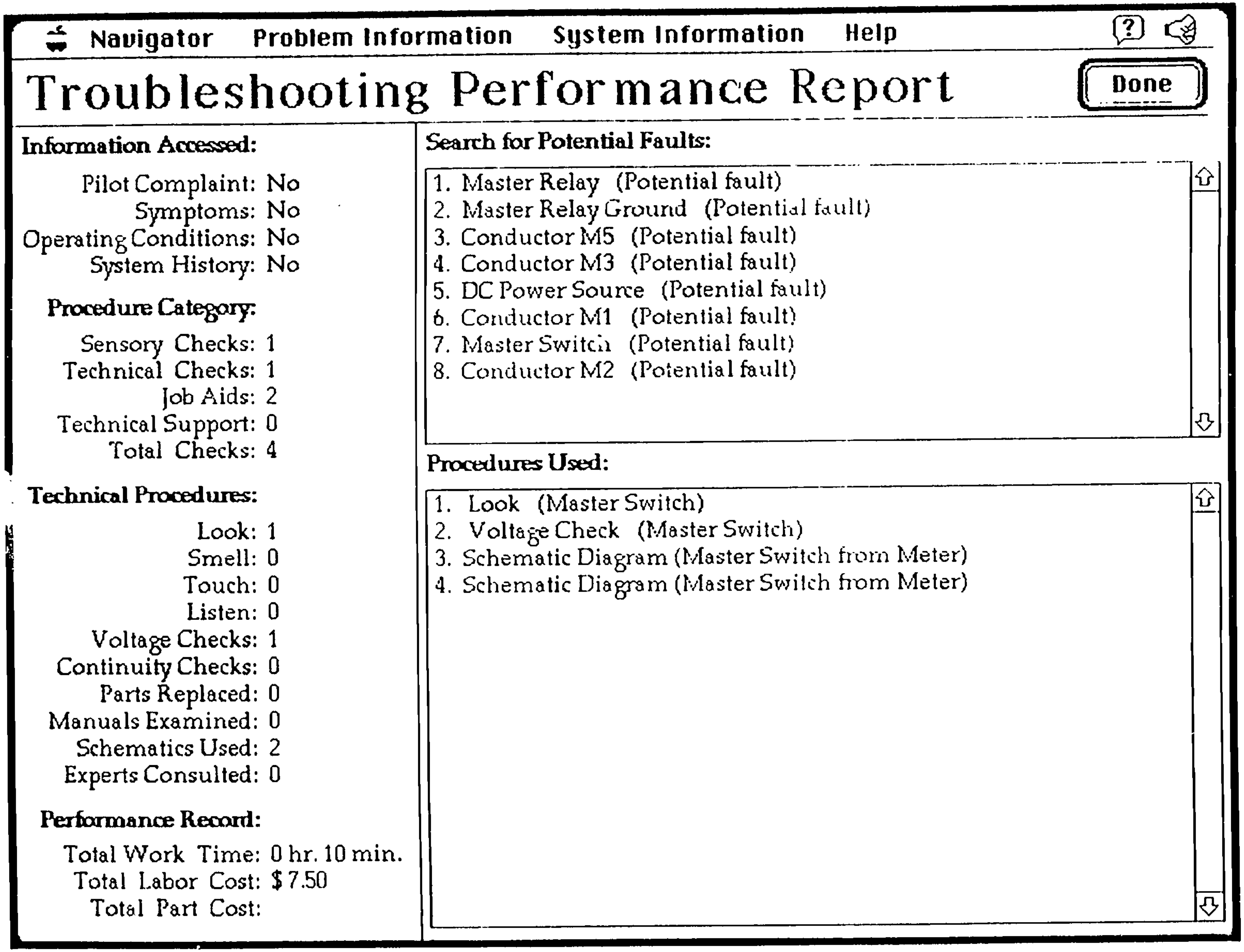
Strategically Focus Learner Attention

Working memory processes what the senses take in. Because the senses are continually flooded with information and attentional resources are limited, individuals must be able to control what information gets into their working memory. The human attentional system is used to prevent memory overload by ensuring that only the information which is "attended to" will be put into working memory.

Attentional focus has been described as a prerequisite for learning (Grabe, 1986). One way of easing the load on working memory is to guide learners to direct their attention towards the most critical information so that it can be encoded. According to Kulhavy, Peterson, and Schwartz (1986), any procedure that directs attention to the instructional content increases the probability that learners will learn the intended material.

Experts have been found to notice relevant and subtle features of events that are not recognized by novices. An important goal in the process of facilitating development toward expertise is helping novices notice relevant features of problems. Novices need to become sensitive to features and dimensions that otherwise might escape their attention.

Figure 7
Troubleshooting Performance Report



Troubleshooting Performance Report

Information Accessed:

Pilot Complaint: No
Symptoms: No
Operating Conditions: No
System History: No

Procedure Category:

Sensory Checks: 1
Technical Checks: 1
Job Aids: 2
Technical Support: 0
Total Checks: 4

Technical Procedures:

Look: 1
Smell: 0
Touch: 0
Listen: 0
Voltage Checks: 1
Continuity Checks: 0
Parts Replaced: 0
Manuals Examined: 0
Schematics Used: 2
Experts Consulted: 0

Performance Record:

Total Work Time: 0 hr. 10 min.
Total Labor Cost: $7.50
Total Part Cost:

Search for Potential Faults:

1. Master Relay (Potential fault)
2. Master Relay Ground (Potential fault)
3. Conductor M5 (Potential fault)
4. Conductor M3 (Potential fault)
5. DC Power Source (Potential fault)
6. Conductor M1 (Potential fault)
7. Master Switch (Potential fault)
8. Conductor M2 (Potential fault)

Procedures Used:

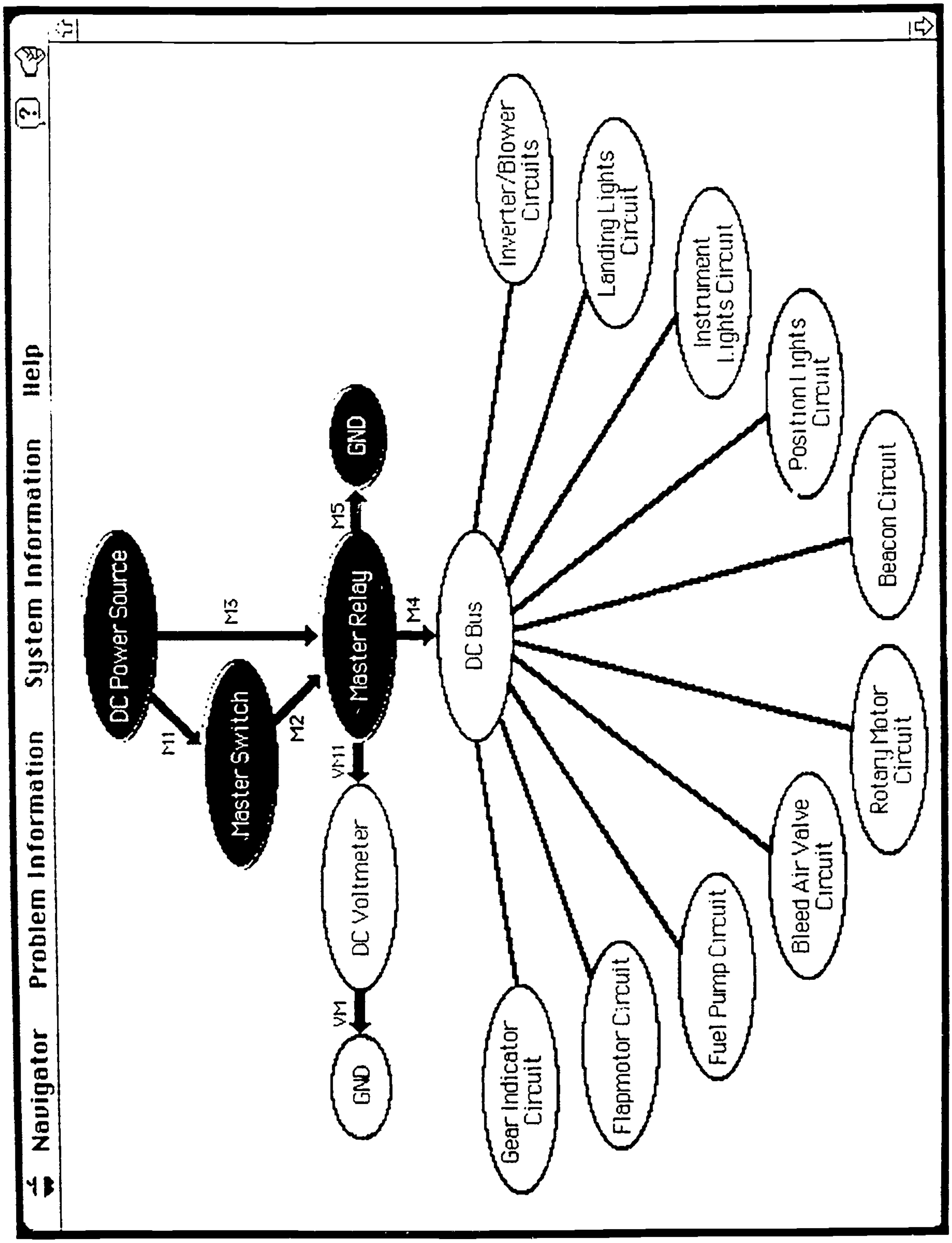
1. Look (Master Switch)
2. Voltage Check (Master Switch)
3. Schematic Diagram (Master Switch from Meter)
4. Schematic Diagram (Master Switch from Meter)

Grabe (1986) describes a number of instructional strategies for guiding learner's attentional focus during the instructional process. The first is a scanning strategy in which learners identify problem components, compare a target problem to a set of alternative features for each component, and then eliminate those alternatives that do not match. A second strategy involves devising ways to help learners identify important sources of information and to avoid distracting, irrelevant information. A third strategy uses highlighting of attentional targets with bright colors, loud sounds, and novelty.

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 8). The student uses a mouse to point to a location on the screen image of the functional flow diagram where the fault may exist. When the student clicks the mouse button at that location, the computer will highlight that portion of the diagram if it could contain the fault. As the student selects more 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 8

Graphical Problem Space Indicated by Shaded Areas on Functional Flow Diagram



Nurture and Reward Expert Behavior

A synthesis of problem-solving research studies (Bouwman, 1983; Elstein, Shulman, & Sprafka, 1978; Sweller & Levine, 1982) resulted in the development of the *Technical Troubleshooting Model* (TTM) that accurately reflects the cognitive process flow of the troubleshooter when working on a technical problem (Johnson, 1989). This model, as shown in Figure 9, is divided into two main phases: (1) hypothesis generation and (2) hypothesis evaluation. In phase one, the problem solver represents the problem by obtaining information from internal or external sources (see Figure 10). As an internal source, the individual's long-term memory contains both declarative and procedural knowledge (Anderson, 1980, 1982; Glaser, 1984). The external sources could include job aids; technical support; technical evaluations through test procedures and operational adjustments; and sensory-based evaluations including visual, auditory, olfactory, and tactile checks. In the second step of the process, the troubleshooter applies cognitive action to interpret the acquired information and determine its relevance in relation to the problem. Once the problem solver has collected sufficient information, one or more hypotheses may be generated (Elstein et al., 1978; Frederiksen, 1984; Johnson, 1987).

In the second phase of this model, the troubleshooter selects a hypothesis to evaluate. This involves using a variety of search strategies to obtain additional information to support a decision to either accept or reject the proposed hypothesis (Frederiksen, 1984). The selection of these strategies depends on a variety of factors including the troubleshooter's level of expertise, the type of technical system, and the difficulty of the problem. The following list identifies four troubleshooting strategies that are commonly used by technical troubleshooters:

1. *Exhaustive search strategy*—This strategy involves testing all fault possibilities. This method requires very little expertise but is only feasible if the set of possible faults is small. The repair of an old television with vacuum tubes is a good example of the appropriate use of this strategy. Rather than use more sophisticated troubleshooting strategies, a practical solution for fixing the television is to systematically test all the tubes.

2. *Topographic search strategy*—This strategy is similar to using a road map to plan a trip. A topographic search strategy starts at some point in the system and relies on a schematic to trace through the system to locate and test the components.

3. *Half/split search strategy*—This method attempts to eliminate the greatest number of fault possibilities with each test. The half/split strategy involves making a test at the midpoint of the system which reduces the search space to only one-half of the system. The next check will then be at the midpoint of the remaining half of the circuit.

4. *Functional search strategy*—Because this method requires extensive system knowledge and thinking ability, it is the most powerful and most difficult troubleshooting method. As a result, it is usually used when the above strategies have failed. This method involves observing the function of the system and proceeding to a specific subsystem based on that information. This method often involves mental simulation of the system in both normal and malfunctioning states. Information about the system and its components is collected and hypotheses about the fault are formed and tested.

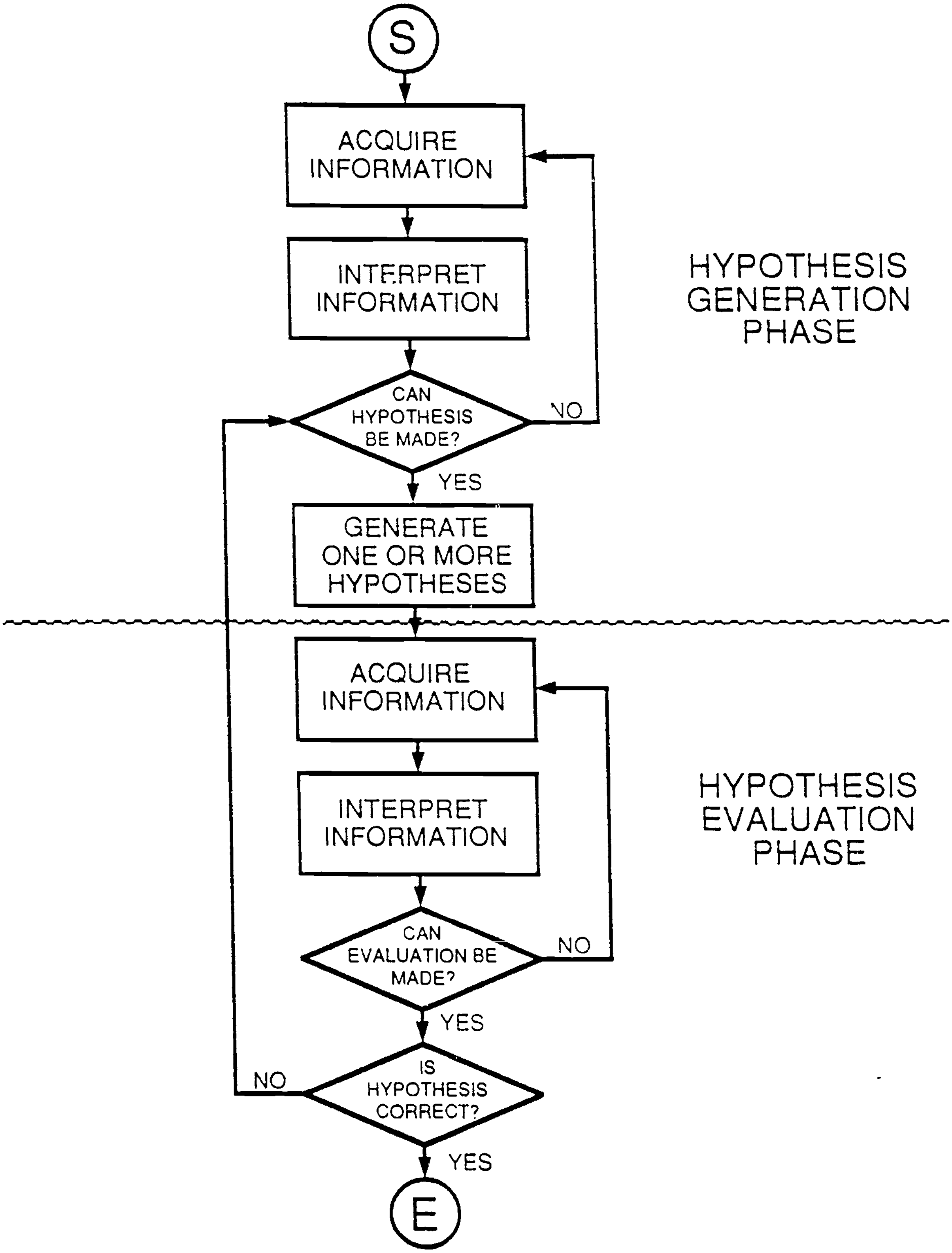
While most troubleshooters rely on one or two favorite strategies, each strategy is useful under certain circumstances. Topographic, exhaustive, and trial and error searches are selected because little cognitive effort is needed. Some methods such as the half/split are selected because they are efficient at eliminating a large number of possibilities. Other reasons for selecting methods include their ease of use, their low cost in terms of time and materials, and their reliance on the availability of spare parts and other resources.

By using these strategies, the troubleshooter will eventually reach a decision point in the troubleshooting process. If the acquired information, and subsequent interpretation, confirms the selected hypothesis, the troubleshooting process ends. If the activity does not result in support of the selected hypothesis the troubleshooter will cycle back to phase one of the model and generate another hypothesis or acquire additional information that can contribute to the selection of a more plausible hypothesis (Johnson, 1987).

The expert approach to troubleshooting as described above provided the framework for the design of the Tutor. Although the students may attempt to solve the problems in any manner they choose, the Tutor encourages them to follow the TTM framework by rewarding them with higher performance scores when they do the things expert troubleshooters tend to do. Rather than begin their problem-solving activity by running equipment checks and procedures, the students are encouraged to begin by collecting

Figure 9

Technical Troubleshooting Model



Source: Johnson, 1987

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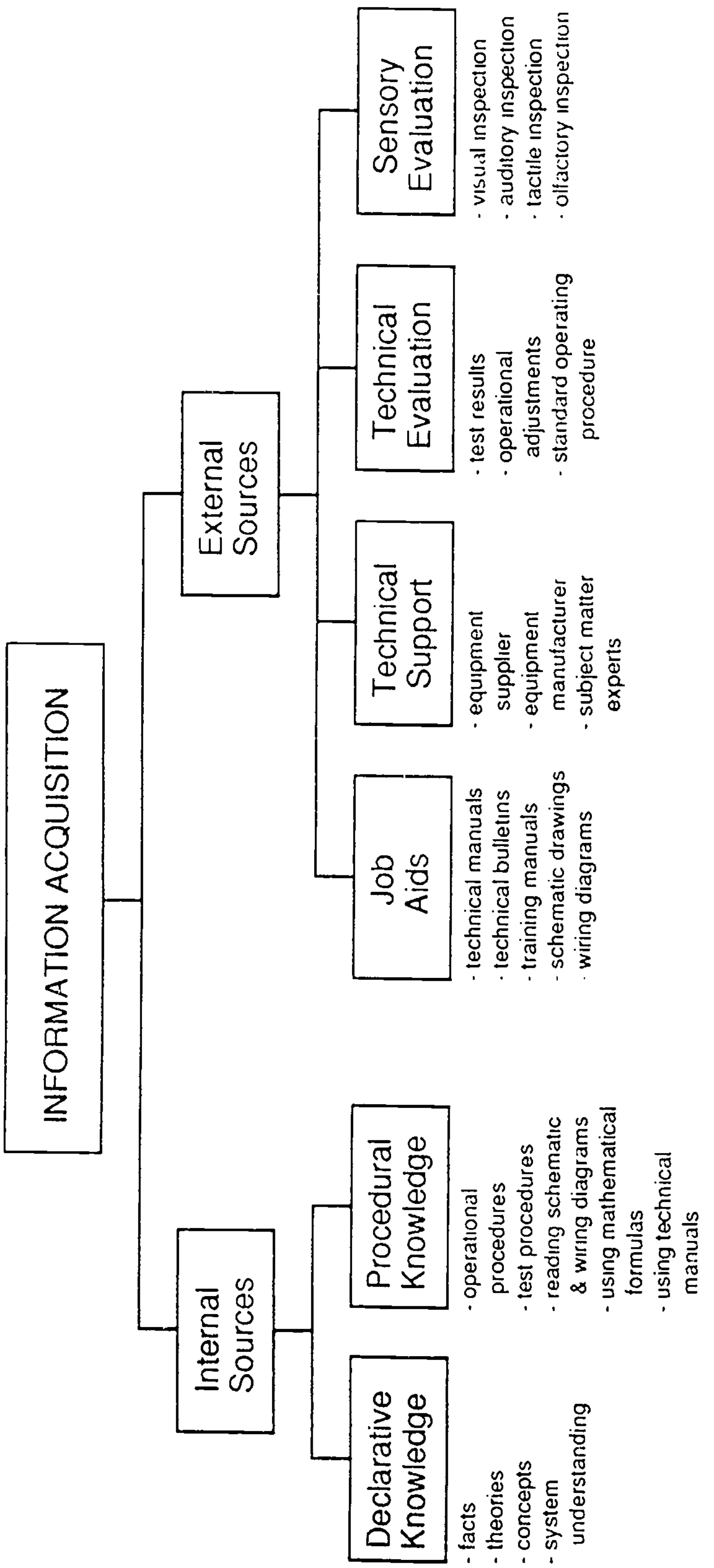
Figure 10

Sources of Information for Troubleshooting



Source: Johnson, 1987

information from a variety of sources and then develop a complete problem space based on the symptoms. This type of cognitive activity early in the problem-solving process encourages the students to reason qualitatively before taking action. This approach is supported by research that has investigated the differences in the ways experts and novices approach problems (Chi, Feltovich, & Glaser, 1981; deKleer, 1985; Larkin, McDermott, Simon, & Simon, 1980). When confronted with a problem, novices tend to immediately look for a solution to the problem. For example, when solving word problems in mathematics and electronic domains, novices typically look for some type of formula that can be applied to the information in the problem. In contrast, experts begin problems by analyzing the problem information from a qualitative perspective. This approach allows the problem solver to gain an understanding of the problem before a solution strategy is selected. Only when the problem is understood does the expert begin looking for a solution.

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 in 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 was offered only once each year, it was necessary to use intact classes. The control group consisted of sixteen students enrolled in the course during Fall semester, 1990, while the experimental group consisted of eighteen students enrolled during Fall semester, 1991. Because data was being compared across two separate semesters, very little interaction occurred between the researchers and the course instructor to assure that the course would be taught in the same way each semester.

The students who participated in this study had successfully completed prerequisite courses in aircraft electrical systems and powerplant systems. The foundation electronics course provided students with basic knowledge of electrical concepts such as AC and DC theory, power generation, circuitry, and solid state devices. The powerplant course covered the theories and operating principles of ignition, starting, and electrical power generating components and systems found in aircraft turbine and reciprocating powerplants. Through these courses, students also acquired limited skills in the use of hand tools and common diagnostic tooling. While these prerequisite courses provided foundation knowledge and introductory skills, they appeared to be adequate preparation for the concepts and skills developed through this study.

Because random selection of subjects was not possible, a variety of demographic and aptitude comparisons were made to determine if the control and treatment groups were similar. Demographic data was collected through a questionnaire administered at the end of the course. There was no significant difference in the mean ages of the two groups, $t(32) = -1.701$, $p>.05$. 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 (ACT) Program examination scores, Survey of Mechanical Insight scores, University of Illinois grade point averages, high school class rank, and grades earned in the prerequisite basic electronics course. As shown in Table 1, no significant group differences in aptitude or achievement were identified.

Table 1
Aptitude Indicators for Tutor and Control Group Subjects

	Control Group			Tutor Group			
Aptitude Indicator	*n*	*M*	*SD*	*n*	*M*	*SD*	t^*
ACT Scores	16	24.06	4.64	17	23.65	4.11	.273
Mechanical Aptitude Scores	16	50.06	29.72	12	57.92	26.79	-.721
University GPA	16	3.92	.44	18	3.86	.38	.449
High School Rank	16	70.94	20.37	18	71.11	25.10	-.022
Prerequisite Course Grade	15	3.40	.91	18	3.56	.98	-.560

Note: *All aptitude indicator comparisons are non-significant at $p>.10$.

Procedure

The *Technical 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 at Urbana-Champaign. This course consists of three hours of lecture and four hours of laboratory activities 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 coursework 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 Aircraft 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 any questions related to the operation of the Tutor but not to provide any assistance related to the solution of problems on the Tutor. The supervisor also collected observation data related to the students' behaviors and verbalizations while working on the Tutor.

After completing the Tutor exercises, each student participated in the same troubleshooting performance tasks used with the 1990 control group class. 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 the 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. The students were not told how many faults existed in the system, only that there were multiple faults inserted by the researcher. 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-referenced knowledge examination which also included a demographic questionnaire.

Transfer Task Selection

The apparatus used to determine posttreatment troubleshooting performance was an instructor-developed training board that represents 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, and valves) are mounted on a tabletop board. System power is provided by an auxiliary power unit that also serves other training boards.

The performance tasks were based on specific criteria to ensure representation of certain populations of tasks. A task analysis was used to identify problems that were commonly encountered by maintenance technicians in the aircraft industry. The transfer task problems were carefully selected to ensure that they were consistent with the knowledge and skills expectations of the course. This was to ensure that the control group would be given instruction and practice during the course that was similar to, but not identical to, the transfer tasks. The four problems that were ultimately selected for the transfer task were then compared to the faults simulated in the Tutor. This was to ensure that they were not part of the fault set within the Tutor and, therefore, would not be solved by the tutor group prior to the final evaluation.

Technical problems can be categorized as structural, functional, and behavioral faults (deKleer & Brown, 1983). Although the categorizations developed by deKleer and Brown were modeled, the specific interpretation of those terms is unique to this study. In this study, the terms were intended to represent specific conditions which provide recognizable symptom sets based on the relationship of system components and potential behaviors. Structural problems are the result of architectural faults including inappropriate or nonexistent connections. Functional problems are those that occur when a system component completely fails, 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. These categorizations are not mutually exclusive and the symptomatic conditions that exist as a result of any particular fault could involve any or all of the categories. However, this level of definition does represent distinct populations from which representative tasks can be selected.

Task selection was limited to problems that were not likely to result in immediate solution based on experience or cursory observation. Additionally, each problem was inserted so that it could be specifically 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.

Four faults were selected for the transfer task which represented a range of difficulty and type. The first fault was a simulated open (i.e., concealed piece of transparent tape) in the point contact of the power path to the lamps within the rotating beacon. Although the actual fault was a structural malfunction, the simulated effect was a functional failure of the point contact. The second fault was a misplaced conductor on a relay in the blower motor circuit. This was a structural fault in the most complex subsystem. The third fault was an internally open instrument light switch. This functional fault was not observable from visual inspection. The final fault was an incorrectly wired microswitch in the landing gear indicator circuit. The microswitch terminals provide either normally open or normally closed options and the incorrect selection was made. Both the rotating beacon and landing gear indicator faults included circuitry not presented on the schematic diagram which required subjects to either demonstrate an advanced level of component knowledge or generate new information through the troubleshooting process.

Data Collection and Analysis

Three kinds of data were obtained to determine the effect of the treatment: (1) domain-referenced test scores; (2) verbal protocols from the troubleshooting performance task; and (3) 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 specific 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. Item analysis was then performed to identify content and item weaknesses. Although a reliability correlation was performed ($r = .40$), reliability measures are designed for norm-referenced instruments and are not appropriate indicators for criterion-based instruments (Gronlund, 1985). The item analysis reliability indicator (KR-20) provides little indication of consistency within a criterion-referenced measure. A more appropriate method for determining consistency within criterion-based measures is objective analysis. The examination was reviewed by project and senior staff electronics technicians in the Department of Electrical and Computer Engineering at the University of Illinois for content validity. The domain-referenced test was administered in the last week of classes after completion of the troubleshooting transfer task exercise.

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 (1989). A second rater coded approximately twenty percent of the total protocol data to validate the coding process. The coding of the two raters were compared for consistency with a resultant agreement coefficient above .90.

Surveys, observations, and archival records were also used to collect ancillary data to assess troubleshooting performance and to determine how the students felt about their interaction with the Tutor. A reaction questionnaire was administered after each student completed a few problems on the Tutor during their first session. The researcher designed reaction questionnaire and the interview guide were pilot tested with graduate students who had taken part in the trial runs of the Tutor. An open-ended observation format was selected which required each supervisor on duty to make a written record of observable events occurring during the session.

A personal interview was also conducted with each student after they completed the Tutor. Each interview took an average of about thirty minutes. Subjects were asked general questions about their opinions of the Tutor, prior experience with computers, career aspirations, and views of how the Tutor might have helped them become better troubleshooters. Specific questions related to the difficulty of the troubleshooting exercises, the adequacy of the feedback provided at the end of each problem, the availability of assistance from the computer, and the correlation of the Tutor activities to the course content.

Data from the reaction questionnaire was analyzed by calculating response percentages of each group. A key word analysis was used to compile the interview data followed by frequency counts and percentage comparisons. The observation data was analyzed by noting those events which occurred most frequently.

RESULTS

The purpose of this investigation was to examine the impact of the *Technical Troubleshooting Tutor* on troubleshooting ability. Following a brief description of the treatment characteristics, the results are organized around the research questions by comparing the observed differences between the control and tutor groups in overall troubleshooting ability, electrical domain knowledge, and cognitive processing. Students' perceptions of the quality, effectiveness, and usefulness of the Tutor are also discussed.

Treatment Characteristics

The eighteen students enrolled in AVI 170, Electrical Systems II, during the 1991 Fall semester received the computer treatment. Two computer stations were available for the project which meant that only two students could work at any one time. This treatment group was expected to complete the Tutor in about six weeks but actually took nine weeks, with each subject completing the Tutor project at their own pace.

The tutor subjects averaged five hours and fifteen minutes on the Tutor during which they solved an average of thirty problems. The computer problems took an average of 10.4 minutes to solve while real laboratory problems are estimated to take more than twenty-eight minutes to solve. The computer allowed for a time savings of nine hours and fourteen minutes per student which calculates to a sixty-three percent time savings for simulated versus real problems. As a result, the computer allowed the subjects to complete many more problems in the same amount of time than they could have completed in the laboratory. A potential criticism of this type of research is that any improvements in performance could be attributed to the fact that the treatment group spent more time on task than the control group. While the treatment subjects had the opportunity to work on the Tutor outside of normally scheduled class times, the majority of their work on the Tutor was done during their scheduled laboratory times. The treatment group averaged less than three hours on the Tutor outside of normal lecture and laboratory times. Thus, while it is possible that any knowledge and skill improvements could be attributed to the fact that the tutor group received three hours of work more than the control group, it is unlikely because those extra three hours represent less than a three percent increase in time on task. It appears more likely that the learning gains were the result of the quality of the students' interactions with the Tutor.

The total number of problems completed by each student before being advanced to the next problem type and level depended on their individual performance. Those students who displayed stronger problem-solving skills solved fewer problems and ultimately took less time to complete the Tutor. Those students who experienced difficulties were cycled through additional problems by the computer. Because of the random nature of problem selection by the Tutor, the same problem was sometimes accessed by the student a second time. Repetition of faults simulates the repetitive nature of actual maintenance activity. Technicians see common faults over and over. The repetitive activity required to solve the same problems many times enables technicians to develop the mental patterns that relate symptoms to faults.

Troubleshooting Performance Differences

Near the end of each semester, all students individually participated in a performance task that required them to troubleshoot a faulty aircraft electrical system in which four independent faults had been inserted. Observations were conducted and verbal protocols were collected as the subjects attempted to locate the inserted faults. The verbal protocols were used to validate the researcher observations and verify the problem recognition and solution data.

Ability to Recognize that Faults Exist

A review of the protocols revealed that the majority of the subjects began their problem-finding activity by operating the toggle switches located on the control panel. This initial general search typified the system operation checks that are common in aircraft maintenance and represented appropriate troubleshooting behavior because no other symptomatic information had been provided.

There was no significant difference in the ability of the control and tutor groups to recognize that faults existed in the electrical system, $t(32) = .081$, $p>.10$. All control subjects recognized that a fault existed within the beacon and blower motor subsystems. Only five control subjects failed to recognize that a fault existed in the gear indicator circuit, and only one control subject failed to notice that a fault existed in the instrument light circuit. Similarly, all tutor subjects recognized that a fault existed within the beacon, blower motor, and instrument light subsystems. Eight tutor subjects failed to recognize that a fault existed in the gear indicator circuit. The inability of subjects from both groups to recognize that a fault existed in the gear indicator subsystem is likely due to the fact that the gear indicator does not have a switch on the control panel and the subjects' initial problem-finding activity focused on the operation of the control panel switches. Overall, the control group was able to recognize ninety-one percent of the faults, while the tutor group recognized eighty-nine percent of the faults.

Ability to Locate Faults

The most reliable indicator of troubleshooting performance is the realistic demonstration of that skill. Data from the observations and verbal protocols were used to assess the ability of the subjects to identify the faults in the aircraft electrical system. Correct solutions were recorded on the troubleshooting performance task if the exact component-level solution was discovered and verbalized in the protocols. If a subject identified a solution that would have removed the fault symptoms, but was not at the component level, the performance was judged as correct at the device level. Incorrect solutions resulted when the subject identified a component other than the true fault. When the subject could not arrive at a solution or completed the task with a statement such as "I'm stuck" or "I can't figure this one out," the solution was recorded as "none."

In spite of the fact that both groups of subjects were equally able to recognize that faults existed within the aircraft electrical system, there was considerable difference in their ability to actually locate and identify the faults. The control group subjects solved an average of 1.63 problems while the treatment group subjects solved an average of 2.89 problems at the component level—a seventy-eight percent improvement in troubleshooting success over the non-tutor group. As a group, the control subjects solved only twenty-six of the sixty-four problems (41%) they faced which represents troubleshooting success on less than half of the attempted problems. In contrast, the tutor group subjects solved fifty-two of the seventy-two problems they faced for a solution rate of seventy-two percent. The distribution of correct problem solutions at the component level for each group are shown in Table 2.

Table 2

Solution Frequencies for Control and Tutor Group Subjects

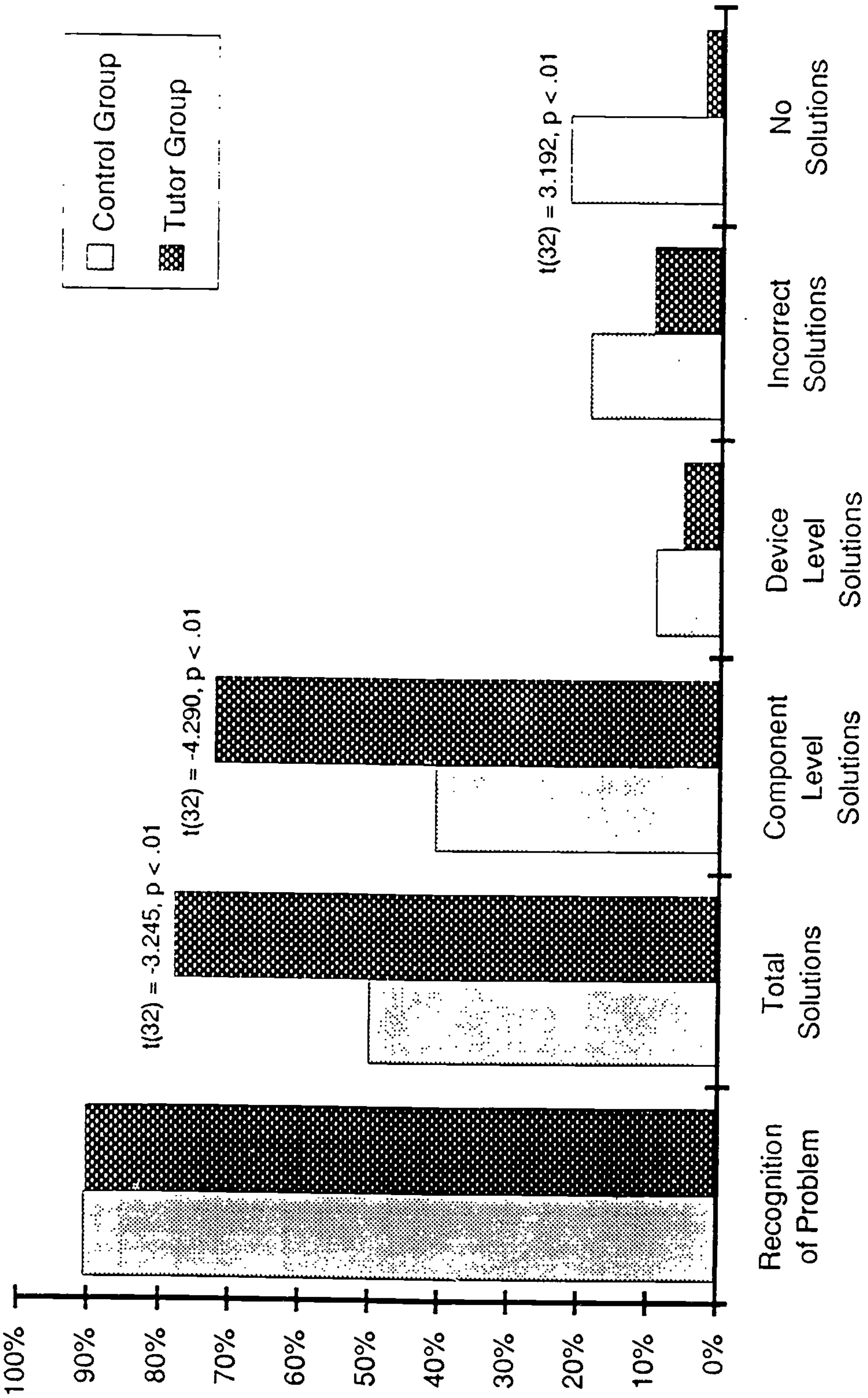
	Control Group Solutions		Tutor Group Solutions	
# of Solutions	*n*	%	*n*	%
1 Correct Solution	9	56.2%	1	5.56%
2 Correct Solutions	4	25%	5	27.8%
3 Correct Solutions	3	18.8%	7	38.9%
4 Correct Solutions	0	0%	5	27.8%

As shown in Figure 11, the ability of the tutor group to solve more problems at the component level than the control group was highly significant, $t(32) = -4.290$, $p<.01$. Although not statistically significant, nineteen percent of the control group's solutions were incorrect while only ten percent of the tutor group's solutions were wrong. The data also shows that the control subjects were much more likely to quit working on the problems before a solution was found. The control group could not arrive at a solution on twenty-two percent of the problems while the tutor group quit on only three percent of the problems. This difference was also statistically significant, $t(32) = 3.192$, $p<.01$.

A hierarchy of fault difficulty can be assumed from these solution results. The blower motor fault, although in the most complex subsystem, elicited the highest level of correct solutions for both the control group (81%) and the tutor group (94%). The instrument lights fault was successfully solved by eighty-nine percent of the tutor group subjects and sixty-three percent of the control subjects. Of particular interest is the beacon fault which none of the control subjects could solve at the component level and was only solved by thirty-eight percent at the device level. These device level solutions included comments such as "replace the beacon" which would result in the replacement of the complete device even though the lamp voltage point contact was the only faulty component. In contrast, the same problem was correctly solved at the component level by seventy-eight percent of the tutor subjects. Eleven of the sixteen control subjects (69%) recognized that the gear indicator subsystem contained a fault but only three of them (27%) could locate the fault. Ten of the eighteen tutor subjects (56%) reported that a fault existed in the gear indicator subsystem and eight of those ten were able to locate the actual fault (80%).

Figure 11

Transfer Task Comparisons



Electrical Domain Knowledge Differences

A domain-referenced test was designed to assess each subject's knowledge of the structure, function, and behavior of the electrical system that was simulated in the performance task. This declarative knowledge examination was administered in the last week of classes after all subjects had completed the course activities and the troubleshooting performance task.

Due to the fact that the tutor group outperformed the control group on the troubleshooting performance task, one might suspect that the treatment group had learned more about the characteristics of electrical circuits and their components. This, however, was not the case. As shown in Table 3, the mean scores on the domain-referenced electrical system posttest examination was 19.88 for the control group and 19.82 for the tutor group out of a total score of twenty-four. This slight difference in mean scores was not statistically significant, $t(32) = .073$, $p>.05$. Group comparisons were also made for the structural, functional, and behavioral subscales of the domain knowledge examination. No significant differences were found between the tutor and control groups for any of the domain knowledge subscales. Although the Tutor seems to enhance the troubleshooting ability of its users, it does not appear to increase their declarative knowledge of electrical system structure, function, and behavior. This finding is consistent with other studies of the relationship between electrical domain knowledge and troubleshooting performance (Johnson, 1987; Bonar et al., 1986).

Table 3

Domain Knowledge Exam Scores for Control and Tutor Group Subjects

	Control Group			Tutor Group			
Domain Knowledge Scores*	*n*	*M*	*SD*	*n*	*M*	*SD*	*t***
Total Exam Score (24)	16	19.88	2.13	17	19.82	1.94	.073
Structural Subscale Score (8)	16	6.75	1.13	17	6.47	1.23	.679
Functional Subscale Score (13)	16	10.63	1.31	17	10.82	1.07	-.477
Behavioral Subscale Score (3)	16	2.38	.62	17	2.47	1.23	-.279

Note: *Number in parentheses is total possible score.

**All exam score comparisons are non-significant at $p>.05$.

Cognitive Processing Differences

Research suggests that expert troubleshooters evaluate problems qualitatively prior to taking action (Chi et al., 1981). Typically this involves making an assessment based on available symptoms in order to be able to predict the possible nature of the problem. The troubleshooter is then guided by the prediction to select an appropriate strategy for identifying the problem. In the process of troubleshooting, the expert constantly monitors her or his action to determine whether the initial prediction made about the problem was correct. From the feedback received in the monitoring process, the expert could review and change strategies accordingly until the problem is finally isolated. This process of thinking about one's thinking is referred to as metacognition (Beyer, 1987).

Metacognition is the focus of a significant portion of the cognitive literature. The term metacognition refers to knowing about and controlling one's own thinking processes (Brown. 1978). Metacognition includes strategies such as self-monitoring, advance planning. self-checking, questioning, summarizing, predicting, generating and evaluating alternatives, and evaluating learning. Metacognition appears to be an important factor in intelligence, effective learning, and problem-solving ability. Brown (1978) states that "the ability to monitor one's own understanding of instructions and messages, whether written or spoken. is an essential pre-requisite for all problem solving ability" (p. 83). Bransford (1979) extends this idea a step further when he states that "the ability to plan and evaluate our own learning strategies seems to be a hallmark of intelligent activity" (p. 244).

In this study, several cognitive operations were used by both the control and tutor subjects. This section examines the cognitive abilities of the subjects to (1) develop and evaluate hypotheses about potential faults, (2) select appropriate troubleshooting strategies, and (3) self-monitor for errors and make appropriate corrections.

Hypothesis Selection and Evaluation

The subjects' protocols were examined to identify the number of hypotheses they generated. Hypothesis generation is a major phase of the Technical Troubleshooting Model and serves as a goal setting process to guide the troubleshooter in the selection of potential faults. Hypothesis statements were those comments made by the subjects that suggested a potential cause of the problem. For the faults built into the troubleshooting performance task, the causes could either be opens, shorts, crossed wires, or burned-out bulbs. Only those statements that suggested a clear goal or hypothesis were considered. Examples of hypothesis statements included "I believe I have an open in the circuit," "something is switched," and "the problem could be burned bulbs." Some subjects repeated their hypothesis statements several times in the course of the troubleshooting process, especially when faced with difficulty in resolving the problem.

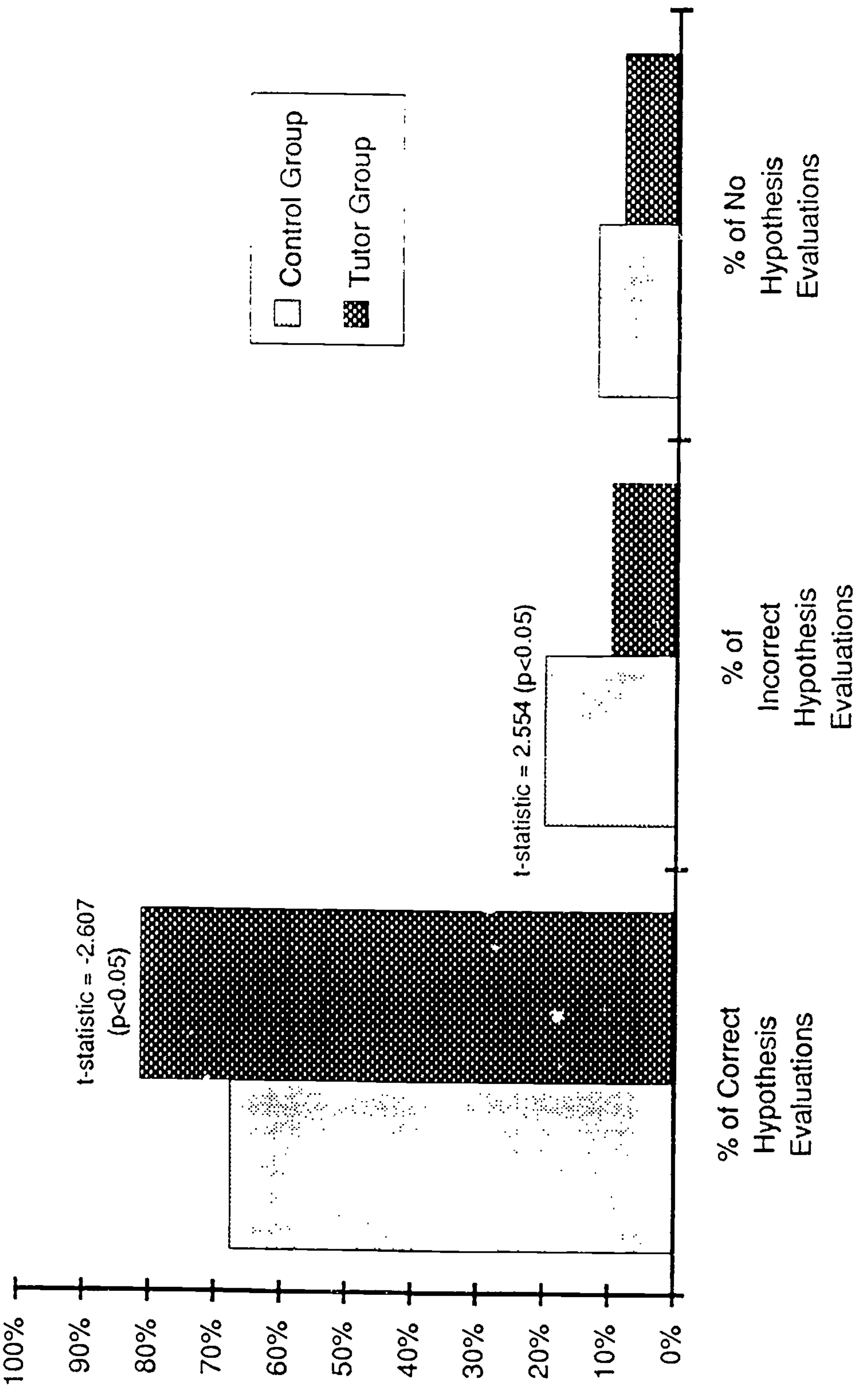
There was no significant difference in the ability of the two groups to generate plausible hypotheses, $t(32) = -.670$, $p<.05$. The control group subjects generated an average of 15.3 plausible hypotheses (SD = 5.59) during the transfer task while the tutor group generated an average of 16.4 hypotheses (SD = 4.69). This suggests that both groups of subjects were equally able to identify potential faults for each problem in the transfer task.

Following the generation of one or more hypotheses that reflect potential faults, the troubleshooter must collect and interpret various types of information to determine which hypothesis is the actual fault. This information acquisition and interpretation process could include making technical checks, examining service manuals, consulting with colleagues, or mentally simulating a functional system. During this evaluation process, the troubleshooter could make a variety of errors. For example, the troubleshooter could incorrectly accept the hypothesis (i.e., by stating that it is the fault when it is not). This error would likely result in the troubleshooter replacing functional parts that are not the cause of the problem. The troubleshooter could also incorrectly reject the hypothesis (i.e., by stating that it is not the fault when it actually is). This error will force the troubleshooter to either waste time by considering another hypothesis or to give up on the problem. These two errors provide a clear indication that correctly evaluating hypotheses is a critical aspect of competent troubleshooting performance.

While there was no difference between the two groups in their ability to identify potential faults, there were significant differences in their ability to correctly evaluate the faults. As shown in Figure 12, the tutor group was significantly better able to correctly evaluate their hypotheses than the control group, $t(32) = -2.607$, $p<.05$. As one would expect, the tutor group was also less likely to incorrectly evaluate their hypotheses, $t(32) = 2.554$, $p<.05$. Although not statistically significant, the control group was more likely than the tutor group to make no decision about the correctness of a hypothesis. These results suggest that the experience on the Tutor enhanced the students' abilities to correctly evaluate the potential faults they considered.

Figure 12

Correctness of Hypothesis Evaluations



Troubleshooting Strategy Selection

The selection of an appropriate troubleshooting certainly contributes to
competent performance. An important difference was ev trategy use between the
control and tutor groups. Tutor group members were mo evaluate the symptoms
in a more in-depth manner prior to selecting a strate oblem space reduction,
incorporated more powerful voltage checks in linea ctivities, and were not
dependent upon a single strategy to facilitate the trouble ocess.

Control group subjects relied on two primary pes: (1) topographic or
linear searches, and (2) visual inspection. Topograp es can be either forward
through the subsystem from a reference point, or rever ame manner using either
visual, voltage, or continuity checks. Additionally e sixteen control group
subjects (38%) utilized a very inefficient variation of phic search strategy that
involved checking the continuity of every conductor nt in the problem space.
This strategy was generally supported by continuity ch gh there were also cases
in which it was combined with redundant voltage c n even more inefficient
process. Five of the control group subjects (31%) wer ly reliant on one strategy
type independent of the problem type. These subjects tively *strategy bound* and
unable to manage the hypothesis generation and eva tivities in an appropriate
manner. Only one tutor group member used the ineffic uity strategy for a limited
time during a single problem scenario and no other p members exhibited that
behavior. There were also no cases within the tuto f a single strategy bound
approach.

While topographic searches can be effective fo ypes of problems, research
suggests that expert troubleshooters evaluate problems tively prior to taking action
(Chi et al., 1981). Functional evaluation is an effec ubleshooting strategy that
involves qualitative evaluation of faulty systems (Rasm Jensen, 1974). The use of
a functional evaluation strategy generally results accurate problem space
representation and increased efficiency in fault is Through this functional
evaluation strategy, the troubleshooter limits the size problem space through a
thoughtful analysis of the circuit without using system i ive checks. The strategy is
completely supported by a logical evaluation that is base the symptomatic conditions
and a review of system diagrams. Some form of functiona aluation was used by nine of

the sixteen control group subjects (56%) and fourteen of the eighteen tutor group members (78%).

Every member of the tutor group demonstrated an ability to incorporate voltage checks within their linear search process. The ability to use this type of information acquisition effort has important advantages over the continuity check favored by many members of the control group. Voltage measurements enable the troubleshooter in an open circuit problem to quickly reduce the problem space and have an indication of circuit behavior based on the voltage readings.

It was noticed that subjects in both groups transferred their experiences gained in one problem to the next. This type of behavior appears to be an instance of the *Einstellung effect* (Luchins, 1942). Einstellung is the mental set which induces a person to use an action or skill that had just been used successfully in another problem. In other words, when an individual has performed one action repeatedly (i.e., practices the action), the individual has a tendency or mindset to continue using that action even when it is no longer the appropriate behavior. While the Einstellung or *history effect* is often a negative consequence of practice, it was used positively by several subjects. This history effect was observed in limited cases in both groups. For example, when a subject found that the reason the beacon was not working was due to an open in the device, that same type of fault was typically searched for in the next problem. Two subjects in the control group and one in the tutor group immediately checked the connections on the beacon circuit relay after finding a mis-wired relay in the blower subsystem. One tutor subject used this history effect to positive advantage. This subject who found that a jumper wire was helpful in obtaining a solution in the Instrument Lights problem, transferred that strategy to the Gear Indicator fault on which he had previously failed to obtain a solution. In this case, the history effect resulted in a correct solution.

The tutor subjects also used a more mature troubleshooting strategy process by reverting to trial and error on the Gear Indicator fault when they were unable to collect relevant information from other methods. The trial and error efforts were not general "shotgun" approaches, however, in that these efforts were directed at specific conductors or components and not larger segments of the problem space.

A clearer picture of the troubleshooting process is developed from a study of the strategies and methods employed in that process. Strategies serve as a general framework supporting the hypothesis generation and evaluation process through management of information acquisition efforts. The ability to select the appropriate strategy is an essential element of the troubleshooting process. Weak strategies such as visual inspection can only find the most symptomatic faults, and a strict topographic search can easily miss a problem that is representative of the behavioral type, particularly additive faults created by marginal components. Tutor subjects were generally able to use more powerful strategies and change their strategic approaches if necessary.

Monitoring Errors and Self-Correction

This metacognitive operation was used to compare the types of errors committed by the two groups during information acquisition processes. An important aspect of the troubleshooting process is whether the troubleshooter realizes that an error has occurred and that self-correction is possible. Significant errors committed by the subjects included redundant checks, checks made out of the problem space, and misinterpretations of the information they acquired.

Redundant Checks

Redundant checks are checks that are not needed because prior information obtained by the troubleshooter should have accurately determined the result of the check. The fewer the number of redundant checks made, the more efficient the troubleshooter tends to be. Two types of redundant checks were commonly made by the subjects: (1) repeated checks and (2) system checks. A repeated check error is committed when the same check is executed more than once. This error results when the troubleshooter does not mentally keep track of the checks already made. A system check error is committed when the troubleshooter executes a check at a level that has been superseded by a previous check. An example of a system check error is one in which a subject executes voltage checks at points in the circuit before a device even though a previous check had already confirmed the existence of voltage at the device.

The number of redundant check errors made by the two groups differed only marginally. The control group averaged 1.04 redundant checks on each problem (59 total redundant checks in 57 problem attempts). Similarly, the tutor group averaged 1.03

redundant checks on each problem (67 total redundant checks in 65 problem attempts). When redundant checks were examined separately, as either repeated or system check errors, no significant difference was observed between the two groups. The control group made twenty-five repeated errors (42%) and thirty-four system errors (58%), while the tutor made twenty-seven repeated errors (40%) and forty system errors (60%).

There was an apparent difference between the groups in their ability to recover from their errors. The control group was able to recover from their errors in only six of the seventeen problems where redundant errors occurred (35%), while the tutor group was able to recover in eleven of the thirteen problems where redundant errors occurred (85%). This finding suggests that the tutor group subjects were both more aware of their errors and had the ability to correct them.

Checks Made Out of the Problem Space

Checks made out of the problem space are information gathering efforts that should not have been done because the acquired information would be of no use to the troubleshooter. This type of check would be conducted by a troubleshooter who had made a wrong hypothesis selection or may have guessed in the hope that one of the checks would reveal something. A good troubleshooter is one who makes few or no errors of this type.

Observations of the two groups on how well they were able to stay within the problem space reveals a marginal difference between them. The control group averaged 3.11 "out of the problem space" checks on each problem (177 wrong checks in 57 problem attempts) while the tutor group averaged 2.34 "out of the problem space" checks on each problem (152 wrong checks in 65 problem attempts).

Misinterpretations

These are errors that resulted when the troubleshooter arrived at a wrong solution due to misinterpretation of problem information. Misinterpretation errors were classified into two types: (1) problem management and (2) knowledge deficit. Problem management errors are inadvertently or carelessly made even the troubleshooter knows how to perform the task. Knowledge deficit errors arise from a subject's lack of knowledge when conducting specific checks or interpreting results. The most common problem management errors involved forgetting to change the meter function switch and forgetting to switch system power on or off. The most common knowledge deficit errors occurred during either meter reading or interpreting acquired information. This erroneous interpretation of the acquired information would lead to a wrong conclusion about the cause of the problem.

On the whole, the tutor group made fewer misinterpretation errors (30 errors: 7%) than the control group (48 errors; 11%). The tutor group subjects also exhibited much stronger ability to recover from misinterpretation errors when they did make them than the control group. In forty-eight misinterpretations, the control group subjects were able to correct their errors only seven times (15%), while the tutor group self-corrected twenty times (67%). A closer examination of the data reveals that the misinterpretations did not occur uniformly across the subjects and problems. For example, one single subject in the control group made twelve misinterpretations on one problem and five on another. When the misinterpretation errors are recorded by the number of subjects who committed them in order to avoid the distortions that could be caused by a single subject, it was found that the tutor subjects still committed fewer errors and had a better recovery rate from their errors.

Eight tutor group subjects committed problem management errors compared to four subjects in the control group. All of the tutor subjects who made problem management errors recovered from them and finally solved the problem while only one control group subject was able to recover from the error and solve the problem. Out of a total of sixty-five problems attempted by the tutor subjects, knowledge deficit errors were committed in seven of the problems (11%). For the control group, knowledge deficit errors occurred in twenty of the fifty-seven problems they attempted (35%). Thus, it appears that the enhanced ability of the tutor group subjects to solve the troubleshooting problems may have been due, in part, by their greater ability to recover from their mistakes.

Student Perceptions of the Tutor

In addition to the collection of comparative performance data, observations of the students as they interacted with the Tutor were conducted to obtain formative evaluation data. Interviews were also conducted with twelve of the eighteen students in the tutor group after they had completed the Tutor. Because the Tutor was in its development stage, this formative evaluation was crucial for future improvement of the *Technical*

Troubleshooting Tutor. The following discussion of the evaluation results are organized around the key questions that were the focus of the evaluation.

Student Enjoyment of the Tutor

After completing the Tutor, ten of the twelve students who were interviewed (83%) stated that they enjoyed working with the Tutor while two students (17%) did not. Eleven of the twelve students said they would most definitely recommend the Tutor to others. Of the two who did not like the Tutor, one stated that he found "the system difficult to understand" but nevertheless he felt the practice would lead to less time in the field and that he would recommend it to others. The second student who did not like the Tutor said it was because he "preferred working on actual live projects." When the students were asked what they liked about the Tutor, a wide range of factors were cited. Most students stated that they liked the graphics, the user-friendliness of the program, and the fact that everything they needed for troubleshooting was in front of them on the screen.

Student Perception of the Difficulty of the Tutor

The students were asked to indicate the level of difficulty of the problems they encountered in the Tutor. Ten (83%) students found the problems challenging while two students (17%) said they were not challenging. The majority of the students felt that the problems became progressively more challenging as they advanced through the Tutor. One student who thought the problems were easy said "the most challenging thing was learning how the computer wanted you to do things." Those students who thought the problems were challenging expressed their views in a variety of ways. One student said, "they were pretty challenging, you had to really sit and think." Another student stated that the problems "were challenging before I got the hang of it. Later it was possible to pick up the solutions by reading the problem information. Towards the end they were harder but I was now more systematic."

It was interesting to observe the different reactions of the students as they attempted to locate faults on the Tutor. Difficulty with a problem often evoked some swearing while successful solutions brought out displays of happiness that were manifested by laughing and talking to oneself, the student working on the next computer, or to the supervisor.

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Student Use of the Help Features in the Tutor

After completing the Tutor, the students were asked how much use they made of the help, system, and component information modules in the Tutor and how adequate they found these to be. Seven students (58%) said they did not use the "HELP" feature built into the program at all while four students (33%) reported that they used it a few times. Most of the students said that they did not use it because they got all the help they needed from the supervisors. A few said that accessing the information would cost "money and time" and would, therefore, lower their overall performance. Several students indicated that they already knew much about the system and its components and therefore they did not need to access that information. The one student who often accessed the supplementary information in the Tutor said that he obtained "very helpful clues" from it.

Changes in Students' Level of Troubleshooting Competence

After completing the Tutor, the students were asked whether they felt the Tutor had made them better troubleshooters. Nine of the twelve students interviewed indicated that they thought it had helped them. Those who felt the Tutor had improved their skills had some positive things to say about it. One student said it "helped me organize my planning. I was more random before" while another student stated that he could now "narrow down [problems] a lot faster." Yet another student said "he would probably use more sensory checks now." Another student commented that "It's a very good idea. It helps one sort out problems in a very efficient procedure."

Changes in the Students' Perceptions of Electrical Systems Courses

Nine of the twelve interviewed students indicated that they felt the Tutor had improved their perception of the electrical systems course. Some of the students reported that their prior experience in the prerequisite electrical course was disappointing and they, therefore, expected to fare even more poorly in the present course. However, they found that the opportunity to solve a large number of simulated problems on the Tutor made them feel more positive toward the domain of electricity. One student said that he "was previously terrified of electricity. The last course was too abstract." Another student captured the view of most of the others when he said "I did not do well in basic electricity [but] I now have more confidence."

DISCUSSION

The results of this study show that the students who worked on the *Technical Troubleshooting Tutor* became more effective and efficient troubleshooters than those students who did not have the same opportunity. With an average of only five hours on the computer, the tutor group showed a seventy-eight percent improvement in actual troubleshooting success over the control group. In comparison to the control group, the tutor group appeared much more determined to locate the faults and displayed greater confidence in their troubleshooting ability. The tutor group also displayed a much higher level of competence in meter usage and troubleshooting strategy selection. In cases where the subjects made troubleshooting errors, the tutor subjects were better able to correct their mistakes and eventually solve the problem. While differences were found in troubleshooting performance, no statistical differences were found between the two groups in domain knowledge as measured by a domain-referenced examination. These results suggest that the Tutor improved the cognitive and metacognitive processes of the tutor group but not their declarative knowledge base as measured by conventional means.

Why did these students become better troubleshooters? This is a difficult question to answer because the Tutor is a comprehensive instructional tool that contains numerous pedagogical strategies that are supported by educational research. While this study did not attempt to identify the specific aspects of the Tutor that made it successful, it may be beneficial to speculate about its most effective features to guide future research in this area.

The primary strength of the Tutor is that it provided students with a *structured practice environment*. Students were confronted with problems that were challenging, yet were within their ability range. As students proceeded through the problems, they were given corrective feedback and guidance when it was most needed. This structured practice environment allowed the students to solve many problems in a short amount of time. In effect, the Tutor provided students with the opportunities, experiences, and feedback that could be offered by any good instructor if they had an awareness of the essential cognitive processes for troubleshooting and the time, equipment, and facility resources available.

The Tutor problems themselves were also structured in a way that facilitated the use of an expert approach to troubleshooting. The students were encouraged to perform like experts and were rewarded for doing so. This meant that the students were taught to access as much information about the problem as possible, to use that information to identify potential faults, and then to systematically perform checks that would verify the fault. Again, the Tutor coached the students through the desired troubleshooting process in the same way an effective teacher would guide students through a similar process.

It is difficult for instructors to turn traditional lab settings into structured practice environments. Troubleshooting practice simulators must be developed and sufficient numbers of tools and equipment are needed. Students must be kept active in the lab even though there are rarely enough work stations for all students to become engaged in actual troubleshooting activities. To work around this problem, instructors typically assign students a variety of related, but not troubleshooting-specific, tasks that will keep them busy in the lab. The use of a computer tutor can easily increase the number of work stations in a lab and allows students to practice troubleshooting outside of lab time. Even if enough high quality work stations for troubleshooting practice are developed, considerable student time will be wasted by the extensive physical manipulations that occur when working with real equipment. A strength of the Tutor is its ability to emphasize only the cognitive processes of troubleshooting by removing the need for assembly and disassembly operations. As a result, the Tutor is able to condense the time frame needed to develop troubleshooting expertise.

Implications for Vocational and Technical Curriculum and Instruction

This study was designed to identify, refine, and evaluate innovative ways of teaching technical troubleshooting. As a result, the findings from this study have implications for vocational and technical curriculum development and instructional delivery. The following recommendations are based on the results of this study and should be used to modify and improve vocational and technical curriculum and instruction:

- *Troubleshooting instruction should place less emphasis on theory and more emphasis on troubleshooting skill development.* Many people seem to believe that the possession of theoretical knowledge is required for competent performance. While a theoretical knowledge base may be important, this study and others (Johnson, 1987; Lesgold et al, 1986; Rasmussen & Jensen, 1974) show that there is little relationship between theoretical knowledge and high-level troubleshooting performance. If an instructor's goal is to prepare students who possess strong troubleshooting abilities, then the curriculum and the instructional activities must emphasize the knowledge and skills that are most needed by troubleshooters. This means that instructional designers should primarily focus on system-specific content and troubleshooting strategies and emphasize only the theories that are fundamental to troubleshooting.

- *The processes and skills of troubleshooting should be explicitly taught to students.* Students cannot be expected to develop troubleshooting skills on their own. Part of the difficulty in developing the cognitive skills needed for troubleshooting is that those processes occur only in the mind and are, therefore, not directly observable to the student. In fact, good thinkers and problem solvers do not even know how they think and solve problems because their thought processes have become so automated that they occur instinctively (Ericsson & Simon, 1984). Because intellectual processes are not directly observable, instructors should explicitly teach troubleshooting strategies by explaining not only what the strategy is, but also how, when, where, and why the strategy should be employed.

- *Students should be provided with extensive opportunities to practice using their troubleshooting skills and strategies.* Research indicates that practice leads to an increase in the speed of task completion and a decrease in the error rate (Phye, 1986). Through practice, students learn from their successes and failures and they begin to develop the ability to process information automatically. Practice is essential to the development of automaticity of information processing and skilled performance. Practice enables the student to proceed through the stages of skill acquisition, from a beginning stage in which information is consciously processed, to a stage in which all but unusual information is automatically processed. Processing automaticity reduces the load on working memory which allows one to think about other task-related things. Extensive amounts of practice also helps students "overlearn" skills which results in fast and efficient performance.

- *Troubleshooting activities should be developed around real problems, situations, and contexts.* Cognitive research indicates that people learn because of the contextual information in the problem situation. The connection between environmental cues and problem situations provides students the opportunity to process information in a problem-oriented format that enables them to relate the available symptoms to a set of potential faults. Students who learn under such situated or contextual conditions are more likely to spontaneously use their new knowledge in future situations. Consequently, careful selection and planning of the instructional context is of prime importance in instructional design.

Implications for Future Research and Development

This study shows the exceptional possibilities for computer-assisted instruction in vocational and technical education. Through the development of intelligent tutoring systems, vocational and technical education can provide enhanced learning opportunities for students. These computer systems have the capacity to guide instruction by realistically simulating faulty technical systems and coaching students through the process of troubleshooting. These systems appear to be educationally sound and are both time and cost-effective. They also have the potential to eliminate many of the problems that vocational and technical instructors face when trying to plan and coordinate troubleshooting activities in laboratories. The following recommendations are made to guide future development of the *Technical Troubleshooting Tutor* and to expand research in this area by building on the results from this study:

- *The Tutor needs to be further refined and enhanced to make it more powerful and effective.* All computer programs need some form of technical support. The Tutor is no exception. The current version of the Tutor needs considerable support to ensure that the program is running correctly. Refinements of the programming code are needed to eliminate any existing "bugs" and to provide enhanced processing speed. It is recommended that a complete user's guide be created and made available to future users. The guide would describe all of the Tutor features and functions, how to use it, how to interpret the performance feedback, and what to do when faced with difficulties. Such a document would give instructors the confidence to use the Tutor in their courses. Additional faults should be added to the Tutor and more digitized images of components and connections would enhance the appearance of the program. The potential of multimedia technology should also be explored as a way to enhance the Tutor.

- *Provide enough opportunities for the students to become comfortable with the Tutor before allowing the Tutor to assess their troubleshooting performance.* While the students were overwhelmingly satisfied with the briefing they received prior to using the Tutor and subsequent assistance they received from the supervisors, it became apparent that many of the students needed help when they began their initial use of the Tutor a few days after the briefing. Making the students conscious of their troubleshooting performances right from the start seemed to affect their willingness to explore various features of the Tutor for fear of being penalized by the Tutor. It is recommended that several trial problems be provided where performance is not evaluated so the student can explore the features of the Tutor.

- *The quality of the feedback and the final performance assessments need to be refined and extended.* It was observed that some students spent several sessions on the Tutor before they actually understood how the Tutor evaluated their performance. The feedback the students receive about their troubleshooting performance needs to be an accurate evaluation of their performance. If students do not understand why they did poorly on a particular aspect of the problem, they will become confused and frustrated. This is also true if they feel the evaluation is either too harsh or does not reflect their true performance. It is also recommended that the evaluation process be fully explained before the students begin work on the Tutor.

- *Research should be conducted to replicate this study in different fields and at different educational levels.* This study should be replicated with larger numbers of students at different levels of education. The electrical system that is simulated in the Tutor is fairly generic in structure and could be used in any electricity and electronics courses in high schools, vocational centers, community colleges, and industrial training settings.

- *Research should be conducted to identify the instructional strategies within the Tutor that provide the greatest increase in troubleshooting ability.* Because the Tutor is a compilation of many instructional strategies, it is not clear which strategies are most effective. Research that tests individual strategies is needed to enhance our understanding of the pedagogy and to guide future changes in instructional practice.

- *Research should be conducted to test the effectiveness of the Tutor's instructional strategies when implemented by human instructors.* All of the instructional strategies in the Tutor can also be used by human instructors although technical instructors need to be trained in the use of these strategies. Research needs to be conducted to test their effectiveness in helping students develop the desired troubleshooting skills.

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