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Following an analysis of task requirements for successful troubleshooting, this paper considers human abilities, limitations, and inclinations with respect to troubleshooting. Research on the effects of various approaches to the training of troubleshooting is reviewed. The extent to which troubleshooting performance is influenced by instruction is highly related to the level of explicitness of action-related information provided. An approach that forces people to use their system knowledge explicitly is a promising alternative to explicit instruction in algorithms or diagnostic heuristics, but such an approach is not supported by data from transfer studies. A combination of the two approaches may be the most effective means of teaching troubleshooting, and research evaluating the soundness of this idea should be conducted.

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REVIEW AND EVALUATION OF EMPIRICAL RESEARCH IN TROUBLESHOOTING

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REVIEW AND EVALUATION OF EMPIRICAL RESEARCH IN TROUBLESHOOTING

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FOREWORD

This work was conducted by Search Technology, Inc. under the Augmented Maintenance Training Project, On-site Training, Work Unit RF63-522-801-002-03.44 and sponsored by the Office of Naval Research.

This paper defines the current state of research on the subject of fault isolation training of military technicians and establishes a benchmark for continued research. It was originally published in the Journal of the Human Factors Society, Vol. 27, No. 5, and is being reprinted by Navy Personnel Research and Development Center for wider distribution.

The contracting officer's technical representative was George Lahey.

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Technical Director

SUMMARY

Background

Data from the field and from the formal schools indicate that troubleshooting skills do not transfer from one system to another and that retraining becomes necessary whenever technicians are assigned to maintain an unfamiliar system. Detaching personnel from their units to send them back to school results in loss of operational readiness and excessive costs. A way to avoid both the excessive costs and the loss of operational readiness is needed.

Purpose

This effort was conducted to review the literature on troubleshooting training, assess the effectiveness of current methods, and establish a basis for further research.

Approach

This literature search focused on data regarding the individual skills needed for successful fault isolation with emphasis on the training issues involved. Four sources were consulted: PSYCHINFO (the online data base from the Psychological Abstracts), the NTIS data base, the personal files of the authors, and personal and professional contacts. Literature that did not specifically involve training issues, including the use of job aids, was not reviewed. About 80 reports and articles relevant to troubleshooting, problem solving with test equipment, problem solving in technical schools and that presented actual performance data were examined.

Results and Conclusions

The successful troubleshooter must be able to (1) repair and replace components, (2) conduct tests, and (3) select an appropriate strategy. The last area seems to pose the greater challenge to instructional designers seeking to facilitate transfer of training. The themes arising in the literature with regard to selection of strategies are that (1) humans are not good at judging probabilities, (2) performance degrades as systems become larger and more complex, (3) performance degrades also in the face of time constraints, (4) presentation of theory of operation generally does not improve performance, and (5) proceduralization improves performance. Because recent research does not address the problems of transfer of training, the utility of high-technology troubleshooting training techniques in the real world has not been demonstrated.

Recommendations

Troubleshooting research studies need to concentrate on ways to proceduralize the troubleshooting task, instill the use of effective algorithms and heuristics, and provide effective practice in logical troubleshooting. The prerequisites for effective transfer of training to the actual equipment also need close attention.

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Review and Evaluation of Empirical Research in Troubleshooting

NANCY M. MORRIS *and* WILLIAM B. ROUSE, *Search Technology, Inc., Norcross, Georgia*

Following an analysis of task requirements for successful troubleshooting, this paper considers human abilities, limitations, and inclinations with respect to troubleshooting. Research on the effects of various approaches to the training of troubleshooting is reviewed. The extent to which troubleshooting performance is influenced by instruction is highly related to the level of explicitness of action-related information provided. An approach that forces people to use their system knowledge explicitly is a promising alternative to explicit instruction in algorithms or diagnostic heuristics, but such an approach is not supported by data from transfer studies. A combination of the two approaches may be the most effective means of teaching troubleshooting, and research evaluating the soundness of this idea should be conducted.

INTRODUCTION

The task of troubleshooting may be described rather simply. Given that a system is not functioning properly, the troubleshooter must attempt to locate the reason for the malfunction and must then repair or replace the faulty component. The level of specificity with which the source of the problem is identified depends on the troubleshooter's role and the current demand characteristics of the situation. For example, the troubleshooter may elect to replace a component or module, or perform some compensatory action to enable the system to continue functioning temporarily.

What skills are required to troubleshoot? Insight into the abilities necessary may be gained by considering what the trouble-shooter is expected to do. If repair of the system is expected, then the troubleshooter must be able to *repair or replace system components.* Depending on the actions required to do so, various abilities may be needed. For example, the troubleshooter may be expected to identify components, use hand tools appropriately, and/or perform relatively simple actions, such as soldering a connection. The ability to replace/repair system components is largely system-specific, particularly if components must be identified. Skills required are generic to the extent that the systems encountered by the troubleshooter contain similar components and require the use of the same tools.

It seems possible, at least in principle, that someone having only the ability to replace parts could successfully troubleshoot a system. The troubleshooter could simply replace parts until the system was repaired. Of course, if the malfunction involved adjust-

ment problems rather than defective components, this approach would not be successful. In addition to these limiting conditions, a replace-until-fixed approach would often be undesirable because of the accompanying expense of repairing the system; a number of unnecessary replacements would be expected to occur if such an approach were used. Therefore, the ability to *make tests* in order to eliminate components from consideration is desirable in a troubleshooter.

There are several important aspects of making tests. The troubleshooter should be able to identify the tests that would supply the information desired, identify and access test points, select and use test equipment appropriately, and make inferences as to the results of each test (e.g., the component is good or bad, or the reading is abnormally high or low). As with the ability to replace or repair components, the ability to make tests is system-specific in many respects (e.g., the ability to identify test points and make inferences as to whether a given reading is off or normal). Abilities required to make tests are generic to those systems in which similar tests may be made. For example, the use of an oscilloscope may be very useful in a variety of electronics troubleshooting problems but may not be helpful at all in diagnosing problems in a chemical plant.

There is another "ability" that seems to be helpful in troubleshooting. This is the ability to search for the problem in a systematic manner—in short, to *employ some kind of strategy* in searching for the source of the difficulty. Depending on the strategy selected, other abilities are required. Troubleshooting strategies may take many forms, from simply starting with the component nearest to the troubleshooter and tracing back to the source of the problem, to generating hypotheses based upon knowledge of the system and symptoms and identifying tests to confirm or reject those hypotheses. Troubleshooters may also employ heuristics (i.e., rules of thumb that are useful for solving a problem), adopt a half-split or bracketing approach, or follow a predetermined set of procedures. Intuitively, it seems that troubleshooting strategies have more potential generality than does knowledge of how to make tests or replace parts, although troubleshooting strategies may be very system-specific (e.g., testing a particular component first because it has a high failure rate).

Good versus Poor Troubleshooters

The importance of these three general abilities to successful troubleshooting is illustrated by the results of studies in which effective and ineffective troubleshooters have been compared. For example, Saupe (1954) observed technicians repairing radio receivers and noted that poor troubleshooters had more incorrect hypotheses and pursued incorrect hypotheses longer than did good troubleshooters. They were also less likely to recognize critical information as such and tended to make fewer checks before accepting a hypothesis as correct. There were no apparent differences between good and poor troubleshooters in their ability to perceive symptoms completely and correctly. Both groups made approximately the same number of errors using test equipment and they duplicated checks equally often.

Saltz and Moore (1953) observed technicians who had been classified by their supervisors as either good or poor troubleshooters, and they noted several strategic hindrances to effective troubleshooting. Ineffective troubleshooters tended to avoid difficult checks, made difficult checks when simpler checks would have been sufficient, made repeat checks needlessly, made irrelevant checks, and omitted relevant checks. Saltz and Moore also observed that good troubleshooters knew more about the functioning of the equipment and were better able to use test equipment properly.

Highland, Newman, and Waller (1956) re-

ported that successful and unsuccessful troubleshooters required approximately the same amount of time to solution and made the same number of tests, but that they differed in the tests they made. Good troubleshooters made fewer repetitive checks involving variation of controls, and more repetitive checks of other types. They were also more likely than were poor troubleshooters to use schematics on the problems they missed, and they generally appeared to use a more varied attack in solving problems.

Baldwin (1978) summarized research analyzing radar mechanics' weaknesses, and reported a number of differences between effective and ineffective mechanics. For example, ineffective mechanics made fewer checks involving manipulation of control settings and generally failed to observe all gross symptoms. In contrast, they used schematics earlier and more frequently than did effective mechanics, and they made more circuitry checks and measurements involving test equipment. After localizing a problem, ineffective mechanics spent more time before attempting replacement, required a longer time to find physical locations of components, and made more errors in repair or replacement of components. Once repair was complete, ineffective mechanics did less checking to verify repair and failed more often to return the system to operational status.

Similar observations have been noted by Glaser and Phillips (1954), Moore, Saltz, and Hoehn (1955), and McDonald, Waldrop, and White (1983). As an interesting note, Glaser and Phillips reported that although failure to solve problems was associated with strategic shortcomings, such as insufficient relevant tests, more than 20% of all such failures could be attributed to faulty inferences (i.e., misinterpretation of an appropriate test).

Summary. It is possible to summarize the characteristics of poor troubleshooters relative to the three general abilities cited as being important for successful troubleshooting. With respect to repair and replacement of components, ineffective troubleshooters demonstrated a lack of elementary knowledge and were poor in executing and verifying the results of their work. When performing tests, poor troubleshooters made fewer useful tests and more useless tests and were inconsistent in their consideration of test difficulty. The strategic behavior of poor troubleshooters was characterized by incomplete and inappropriate use of information, ineffective hypothesis generation and testing, and generally less strategic flexibility.

Training Requirements

If we accept the necessity of being able to repair or replace components, perform tests, and employ a strategy, then those responsible for training troubleshooters must provide training in three broad areas. Strategic training would seem to pose the greatest conceptual challenge to the instructor. Repair and replacement training seems relatively straightforward; trainees must be able to repair or replace those components that require it. Training persons to perform tests seems more complicated, particularly if the results of several tests must be assimilated in order to make inferences, but such training is at least constrained by the number of possible tests.

By comparison, one has a great deal of latitude in approaching strategic troubleshooting training. In order to proceed, one must answer a number of questions. For example, should people be trained to employ a particular strategy or should they be allowed to discover their own strategies within some envelope of acceptability? If the use of a particular strategy is desired, can people be taught to use it? What is the best way to teach a given strategy? And finally, what strategy should be taught?

The answer to the last question is complicated by the fact that there is no single ap-

proach that is appropriate to all situations. The best strategy for a given situation depends on the degree to which use of a given strategy can enable the troubleshooter to meet current performance criteria and the facility and willingness with which the human troubleshooter may be expected to employ the approach.

With respect to performance criteria, it is possible to imagine four goals: speed, accuracy, low cost, and efficiency. The goal of efficiency is probably most appropriate as a subgoal for speed and/or cost, since minimizing the number of tests may in turn be a way of achieving these goals. Obviously the criteria noted here are not orthogonal, and all seem desirable. At any given time, however, trade-offs may be made as to which criterion is dominant, and this may determine which troubleshooting approach should be adopted. For example, if time is of the essence or the risks associated with inaccuracy are high, saving the cost of a spare part should not be uppermost in the troubleshooter's mind. On the other hand, if the pace is more leisurely, the troubleshooter may be more concerned about the cost of repair.

HUMAN ABILITIES, LIMITATIONS, AND INCLINATIONS

The troubleshooter's ability to employ a given strategy is related to human information-processing abilities and limitations. It is important that the human's abilities be considered because of the errors that may occur as a result of a mismatch between abilities required and abilities available. For example, suppose it is determined that a half-split approach, which allows maximum information gain per test, is theoretically the best approach for a given problem. If the troubleshooter has difficulty in identifying the set of remaining alternatives following a test, then errors could result in a loss of efficiency and incorrect inferences. Insight into

characteristics of human information-processing that may affect the troubleshooting process may be gained from studies in which people were observed as they solved problems.

For the most part, the studies reviewed in this section involved the solution of relatively simple, low-fidelity troubleshooting problems. Although a variety of media were employed (paper-and-pencil tasks, computer-based simulations, and in a few cases, actual hardware), a characteristic common to many of these problems is that they were context-free, or generic. In other words, they were not intended to be representative of any particular system. For example, in the case of a paper-and-pencil or computer-generated task, "components" might simply be unlabeled rectangles, with lines between rectangles representing functional connections. Typically, subjects attempted to locate faulty components by requesting information about the quality of component inputs and/or outputs.

Effects of Visual Characteristics

One insight gained from these studies is that performance may be affected by the visual characteristics of the problem. Dale (1958) presented college students with a simple paper-and-pencil troubleshooting task and found that initial tests tended to be in the middle of the picture, without regard to functional relationships between components. Students also made frequent tests at bends in component chains, even though such features were irrelevant to component outputs. Dale also noted that his students tended to adopt a pattern-like strategy when searching for a faulty component among unrelated components; however, no such strategy was observed when students were not shown a picture but performed the analogous task of guessing which letter of the alphabet was being thought of.

Brooke and Duncan (1981) studied the troubleshooting behavior of college students as they solved computer-based problems. Connections between components were depicted as straight diagonal lines or as crooked lines composed of vertical and horizontal segments, and "flow" through connections could be either left-to-right or unconstrained. Troubleshooting was faster and fewer diagnostic errors were made when connections were straight lines and flow was left-to-right only.

Rigney and Hoffman (1961) noted that visual clutter had no effect upon subjects' ability to solve paper-and-pencil troubleshooting problems. However, Elliott (1965) reported differences in high school students' performance on paper-and-pencil problems related to the format of the troubleshooting aid (i.e., procedures) provided. Accuracy was greater when subjects used a block diagram rather than a list of actions to take. Problems were also solved more quickly and accurately when the level of detail of the aid was no greater than necessary to solve the problems.

Although all of these studies used simple simulated tasks, the effects that irrelevant problem characteristics may have upon troubleshooting performance are not limited to the laboratory. Wohl (1961) noted that differences in system down time were associated with differences in "packaging techniques."

Effects of System Complexity and Time Constraints

Troubleshooting performance may be degraded by the size and complexity of the system. Brooke and Duncan (1981) noted that increasing the number of components in their generic troubleshooting task resulted in more diagnostic errors made by subjects. Rouse (1978a, 1979b, 1979c), using a task similar to that employed by Brooke and Duncan, reported that subjects departed from optimal (i.e., did not achieve the maximum reduction of the number of alternatives with each test) and took longer to solve problems as network size increased.

Goldbeck, Bernstein, Hillix, and Marx (1957), using a paper-and-pencil task, found that more tests were made as the number of relevant relationships between component chains increased. Rouse and Rouse (1979) reported that the amount of time subjects required to solve context-free problems was highly correlated with the number of relevant functional relationships that must be considered. McDonald et al. (1983) noted similar increases in time required and number of probes made accompanying increases in the complexity of actual electronics boards.

As with visual characteristics, the effects of system complexity are apparently similar across a variety of systems. Wohl (1982) examined available data on time required to repair various systems and devised a model to predict system repair time. One of the parameters of that model is a complexity index, based upon the number of relevant relationships between components.

Feedback loops also appear to present problems for troubleshooters. Rouse (1979a) observed the troubleshooting behavior of four students as they attempted to locate faults in a simple network of components containing feedback loops. A model was then developed to match their behavior. One important parameter of the model, which appeared useful in distinguishing strategies, was the degree to which information in feedback loops was used. Two subjects seemed to ignore the feedback loops and made more incorrect diagnoses than did the other two. Although the results of this study are not strong enough to warrant drawing definitive conclusions, the notion that feedback poses problems for troubleshooters is one with which many instructors will agree.

As a final characteristic, it is possible to note that humans' strategies may be affected by time constraints. Rouse (1978a) varied the amount of time in which subjects were allowed to solve simulated troubleshooting problems. As less time was allowed, the number of tests made by subjects departed from optimal. This effect was observed even when the amount of time allowed was greater than the average amount of time that self-paced subjects had previously required to solve the problems.

Generation of Hypotheses

Many approaches to troubleshooting require the troubleshooter to hypothesize about the possible causes of symptoms. There is some evidence to suggest that people may have difficulty in generating complete sets of hypotheses. Mehle (1980) presented experienced and novice mechanics with scenarios describing automobile problems and asked them to identify all of the potential causes of these problems. While doing so, subjects generated verbal protocols, which were recorded. Their lists of hypotheses were generally incomplete; yet, subjects were frequently overconfident about the completeness of their lists. Gettys, Manning, Mehle, and Fisher (1980) reviewed a series of related experiments using a variety of problems (including Mehle's study) and reported similar results. They also observed that subjects seemed to check hypotheses for logical consistency with available information as they were generated.

Use of Negative Information

There is some evidence to indicate that during the course of troubleshooting, people use positive information (i.e., information about bad outputs) but do not take account of negative information (i.e., information about what has *not* failed). Rouse (1978b) presented a fuzzy-set model of subjects' performance in solving simulated troubleshooting tasks. Although parameters for inclusion in both feasible and infeasible sets (i.e., components that could and could not be the failure) were included, only the parameter related to the criterion for inclusion in the infeasible set was sensitive to differences in performance.

Use of Probabilistic Information

If the sampling behavior of troubleshooters may be used as an indication, then people cannot be viewed as purely Bayesian when evaluating hypotheses. In an experiment conducted by Bond and Rigney (1966), Navy technicians were asked to judge the probabilities of occurrence of various symptoms if certain malfunctions should occur. The resulting fault-symptom matrices were then used in conjunction with Bayes' theorem to predict the sequence of checks that would be made when performing a simulated troubleshooting task. Predictions were in agreement with actual behavior approximately 50% of the time. It was also noted that the degree to which troubleshooting performance was Bayesian was moderately related to the accuracy of the initial fault-symptom matrix generated.

Troubleshooters apparently experience some difficulty in judging the likelihood that various components will fail. Mills (1971) presented subjects with a simple chain of components and asked them to locate the faulty one. Over the course of the experiment, he employed different distributions to determine the probability of failure for each component. Search strategies employed by subjects appeared to be "statistically logical" but were not optimal; over time, subjects appeared to take the current failure probabilities into account, except when the most likely failure was at either end of the chain.

Related information is available from Stolurow, Bergum, Hodgson, and Silva (1955). Prior to implementing a proposed approach

to strategic training, it was necessary to ask instructors to judge the probabilities with which components in aircraft power plants would fail. The approach was not implemented because sufficient agreement between instructors could not be reached.

Individual Differences

A number of the studies reviewed reported that performance was substantially related to individual differences, which often resulted in interactions with training techniques. The influences of three variables have been systematically studied. These are the variables of experience, relevant abilities, and cognitive style.

Experience. It is not surprising that differences in performance related to experience have been observed. After all, it has often been said that practice makes perfect. The role of experience is discussed here because some of the research reports present findings that are not intuitively obvious.

Vineberg (1955/1968) compared the abilities of field-experienced mechanics and recent training school graduates to repair the AAFCS M33 radar. As might be expected, the experienced personnel scored much higher than did the novices on a performance test in which speed of repair was emphasized. An interesting feature of this report was a discussion of the relative speed with which various performance components were acquired. "Energizing and operation" skills were acquired very early, being demonstrated by mechanics of all experience levels. "Field adjustment and preventive maintenance" was acquired somewhat later, becoming relatively stable after 1 to 6 months of experience. "Troubleshooting" developed over a long period of time, continuing to improve through the highest reported experience level of 25 to 48 months. Two interpretations of these differences are possible. One is that these performance components are acquired at different rates and thus require different amounts of practice; the other is that daily experience afforded these mechanics less opportunity for troubleshooting practice, so that various skills were acquired at different times.

Apparently the ability to learn from experience also improves with experience. Rouse (1979b, 1979c) reported that students in the last semester of an aircraft maintenance training course showed positive transfer from an aided to an unaided version of a simple, context-free troubleshooting task. (Aiding consisted of identifying those alternatives that had been logically eliminated by tests.) No such effect was found for first-semester trainees. Note that the experience variable in this research was general troubleshooting experience within a domain and not amount of practice on the experimental task.

Hunt and Rouse (1981) again noticed differences in first- and last-semester trainees in transfer to a context-specific troubleshooting task (which is described in a later section of this paper). Last-semester trainees obtained more information per test in the context-specific problems after training with the aided context-free task. First-semester trainees showed negative transfer, obtaining less information per test. Hunt and Rouse attributed these differences to probable differences in the way the aiding was perceived. The more experienced subjects viewed the aid as helping them, and they were able to determine the principles used by the aid and employ them in an unaided situation. The less experienced subjects simply viewed the aiding as a way to make the task easier for them, and did not learn the aiding principles.

Although experience has been shown to be an important factor affecting troubleshooting performance, differences in performance as a result of experience are less apparent as more troubleshooting guidance is provided. Potter and Thomas (1976) found

that maintenance technicians with experience of six months or less solved fewer problems and used more spare parts than did more experienced personnel. However, these differences were observed only when the problems were accompanied by standard technical orders. When troubleshooting procedures were available, no experience-related differences were observed. Similar results were noted in a study by Elliott and Joyce (1971) in which high school students using a troubleshooting guide were able to identify faults in electronic equipment as effectively as Air Force technicians using traditional manuals.

Abilities and aptitudes. Duncan (1971) noted a difference between subjects with high ability and low ability in their retention of skills learned via troubleshooting a paper-and-pencil simulation with a decision tree. Subjects were classified as having high or low ability on the basis of their pretraining performance of the task. Over a period of 182 days following the removal of the decision tree, performance of the low-ability subjects degraded, whereas performance of the high-ability subjects remained approximately the same. Duncan attributed this to probable differences in the way subjects learned the task. He hypothesized that those people with good retention had learned the rules governing decision tree choices (i.e., a half-split approach), whereas those with poor retention had learned the series of steps by rote.

Goldbeck et al. (1957) observed differential effects of instructions upon performance, dependent upon problem characteristics and individual differences. In evaluating the effects of different types of instruction upon subjects' ability to solve paper-and-pencil troubleshooting problems, they noted that instructions on how to perform a half-split test were sufficient to enable subjects to solve simple problems. For more complex problems, however, differences in subjects'

performance were related to scores on a "problem-solving" test administered at the end of the experiment. Subjects scoring high on that test were still able to solve complex problems with the half-split instructions; low-scoring subjects were able to solve the complex problems only if given additional instructions and practice in identifying the feasible set of alternatives.

Elliott (1965) presented high school boys with performance aids varying in both form (i.e., a list or a block diagram) and level of detail. The boys then attempted to use the aids to solve simulated troubleshooting problems. No systematic differences in speed were observed, but boys with high aptitude (scores of 75–95 on the AFQT-F) were more accurate than those with medium aptitude (scores of 40–60). There was also an interaction of aptitude and level of detail of the aid; the low-aptitude group had particular difficulty in using the aid with a high level of extraneous detail.

In a later experiment, Elliott (1967) provided high school juniors with a troubleshooting guide and observed them as they attempted to solve MTS-2 problems. (The MTS-2 is a hardware generic electronic system.) Subjects were classified as having high or medium aptitude on the basis of the AQE (scores of 80–95 and 50–65, respectively). High-aptitude subjects were slightly better at correctly isolating faulty modules and components. This difference was attributed to their following the troubleshooting guide more closely.

In 1968, Elliott and Joyce reviewed the results of six studies investigating variables related to the design and use of job performance aids. (The two previously noted studies by Elliott were included in this review.) The following relationships between aptitude and performance were noted. First, speed of performance did not appear to be related to aptitude except in one study in-

volving paper-and-pencil troubleshooting tasks and "ambiguous" test results. In that study, high-aptitude subjects (scoring above 75 on the EL scale of the AQE-F) were faster than medium-aptitude subjects (scoring between 40 and 65). Second, high-aptitude subjects were found to be slightly more accurate than medium-aptitude subjects in solving paper-and-pencil problems. Finally, no differences between high- and medium-aptitude subjects were observed in their ability to troubleshoot actual equipment. Elliott and Joyce attributed the failure to find a difference in the latter case to the variety of abilities other than cognitive skills that are required in actual troubleshooting.

An alternative explanation for the general lack of a clear difference between high- and medium-ability troubleshooters was suggested by Henneman and Rouse (1984). In their research, ability and aptitude were found to be poor predictors of performance of a simulated troubleshooting task, although significant regression coefficients were obtained when entered into a regression equation with cognitive style (discussed later). All of the subjects in this research were students at the University of Illinois. Their interpretation was that troubleshooting performance may be related to ability only if some minimum threshold of ability is not present. (Presumably, qualifying for admission to the university assured that the threshold was exceeded.) Beyond that threshold, other factors are more important.

Highland et al. (1956) administered a battery of tests to 360 experienced radar mechanics and then observed their performance as they attempted to solve six problems on an oscilloscope kit. Ratings of their troubleshooting performance were then compared with test results. Highland et al. found that the test that accounted for the greatest proportion (60%) of the variance in troubleshooting performance assessed "technical knowledge" of the oscilloscope. The "electronics fundamentals" test accounted for 40% of the variance, and a test of "reasoning ability" accounted for only 7%.

A study by Demaree, Crowder, and Morrison (1955) is presented as a final note on aptitudes and abilities. They employed a variety of tests to assess the strengths and weaknesses of Q-24 mechanics. Of the many tests they used, a multiple-choice test of "practical job knowledge" was found to have the highest relationship to performance. The aptitude test that had the most validity was that "requiring the mechanic to grasp and find the consequences of complex systems of relationships."

Cognitive styles. A number of measures of cognitive style have been found to correlate with troubleshooting performance. Two dimensions of cognitive style were discussed most often in the studies reviewed. These were field dependence-independence and reflectivity-impulsivity. Rouse and his colleagues (Henneman and Rouse, 1984; Hunt, Henneman, and Rouse, 1981; Rouse and Rouse, 1979, 1982) analyzed the results of research in which subjects solved a number of troubleshooting problems, both in simple simulations and in actual equipment. Measures of cognitive style (scores on the Matching Familiar Figures Test and the Embedded Figures Test) were also available for these subjects. The following results were reported.

First, those subjects who were field dependent were found to be initially slow in solving simulated troubleshooting problems, but became faster with practice until there was no difference between field-dependent and field-independent subjects with regard to the amount of time required to solve problems. Second, subjects categorized as impulsive made more errors in troubleshooting than did those who were reflective. The impulsive subjects did not improve with

practice. This finding was consistent with other reports in the cognitive style literature. Third, as noted earlier, measures of ability (scores on the ACT test) were not significantly correlated with measures of troubleshooting performance; however, significant regression coefficients were found for measures of ability and cognitive style when the measures were combined in a regression equation to predict performance.

Several measures of cognitive style, abilities, and aptitudes were obtained from students in the Navy's Basic Electricity and Electronics (BE/E) school (Federico, 1982, 1983; Federico and Landis, 1979, 1980). The extent to which these measures were predictive of student success in the first 11 modules of BE/E school was assessed via correlations with student achievement and module completion times. For 7 of the 11 modules, measures of cognitive style and/or abilities were found to be more predictive than were measures of aptitude. Measures of ability were more closely related to achievement in the early modules, and other measures were more predictive of performance in later modules. With respect to module completion times, measures of cognitive style and/or abilities were more predictive than were measures of aptitude in all modules. Aptitude measures were more highly related to completion times during the second half of the course. These shifts in the predictive power of each measure were interpreted as reflecting changes in course content.

As a result of these analyses, it was concluded that module completion times and achievement in BE/E school could be predicted from combinations of the measures employed. For example, students high in achievement were found to be discriminating, reflective, high in general and logical reasoning and ideational fluency, and good at numerical operations. Rapid completion times were found to be associated with field independence, high general and inductive reasoning ability, and high ability in mathematics and general science.

Flexibility of closure (i.e., ability to locate hidden figures) and spatial scanning (i.e., speed of visual exploration) were viewed by Rose, Fingerman, Wheaton, Eisner, and Kramer (1974) as abilities rather than cognitive styles, and together they were found to account for a modest but significant portion of the variance in performance of a simple troubleshooting task. In an interesting approach, an attempt was made to improve these abilities in subjects through training (Levine, Brahlek, Eisner, and Fleishman, 1979; Levine, Schulman, Brahlek, and Fleishman, 1980). Training consisted of extended practice with paper-and-pencil exercises such as mazes and figure copying. Training resulted in a difference in only spatial scanning in one study, and no subsequent differences in troubleshooting were noted.

Summary. Individual differences in experience, cognitive abilities and aptitudes, and cognitive style have been shown to be related to troubleshooting performance in a variety of ways. The following statements may be made about the effects of experience. First, in view of the findings reported by Vineberg, experience may be helpful and even necessary if the acquisition of essential skills requires extensive practice, or if the opportunity to practice some skills occurs infrequently. Second, the ability to learn from prototypical examples appears to be related to the experience one has in a domain. Third, experience may also improve the ability one has to learn from feedback related to actions. Finally, lack of experience has less impact upon performance as more guidance in troubleshooting is provided.

The results relevant to abilities and aptitudes may be summarized as follows. First,

high cognitive ability may enable one to learn more from prototypical examples. Second, high cognitive ability is associated with a greater ability to employ a half-split approach on complex problems. Third, ability-related differences in performance are rather small if comparisons are confined to persons having at least some moderate level of ability. Finally, the measures of ability that have the highest relationship to performance are those that test job-related knowledge and skills directly; measures of general aptitude are not very predictive of problem-solving performance on actual equipment.

Regarding the impact of cognitive style on troubleshooting, several measures of cognitive style have been reported to be predictive of success in electronics training courses. When the relationship of cognitive style to troubleshooting performance was investigated, reflective subjects were found to incur less unnecessary cost. Field-dependent subjects were initially slower at troubleshooting but became faster with practice. Impulsive subjects made more errors and did not improve with practice. Finally, training to improve flexibility of closure and spatial scanning did not yield the anticipated positive transfer to troubleshooting.

APPROACHES TO TRAINING

With this perspective as a frame of reference, consider the various training approaches that have been tried and the effects these approaches have had upon troubleshooting performance. In selecting material for inclusion in this review, only those reports that presented data relative to performance effects were used. This criterion was adopted because the goal of this paper is to summarize the state of empirical knowledge about troubleshooting and not to review the many approaches to troubleshooting training.

One way in which the studies reviewed may be categorized is in terms of the primary rationale or goal of the training approach, although explicit statements of this were rarely found. Using this basis, it is possible to identify four general approaches to training, with a salient dimension being the degree to which the troubleshooter is explicitly told what to do. These include: (1) instruction in the theory upon which the system is based, (2) provision of opportunities for troubleshooting practice, (3) guidance in the use of system knowledge, and (4) guidance in the use of algorithms or rules.

In one respect, this order of presentation of training approaches may seem inappropriate. It is possible to view theoretical instruction and opportunity for practice as opposites in terms of system-relevant information supplied to the troubleshooter. The focus of theoretical instruction is description of the functioning of the system; on the other hand, it is possible to provide an opportunity for troubleshooting practice without ever discussing the nature of the system. These two approaches are similar, however, with regard to the *action-related* information provided. In both cases, the troubleshooter is expected to develop an appropriate strategy rather than to follow a prescribed strategy. In the latter two approaches noted (guidance in using knowledge and in following algorithms or rules), the troubleshooter is given more information about how to proceed.

Theoretical Instruction

In this very traditional approach, the troubleshooter is given a thorough description of the functioning of the system and instruction in the theory upon which the system is based. Once provided with this information, the troubleshooter is expected to develop an appropriate strategy for troubleshooting the system. In many of the studies summarized

here, the performance of troubleshooters instructed in theory was compared with that of a control group of persons instructed in some other way. Usually this control treatment consisted of some form of proceduralization. Because proceduralization is the topic of discussion in a later section, it is not discussed at length here.

Schorgmayer and Swanson (1975) varied the nature of written instructions given to trainees in electronics troubleshooting. Some trainees were given a "conventional" account of the functioning of the system, and others were given procedural instructions, with no reference to the way in which the system worked. The investigators found no differences in troubleshooting abilities of the two groups in familiar or unfamiliar situations and no differences in attitude toward the job.

Shepherd, Marshall, Turner, and Duncan (1977) observed process operator trainees' diagnostic behavior after providing them with one of three types of instruction: (1) *no story*, consisting merely of a description of the interpretation of displays; (2) *theory*, including a presentation of the theory upon which the system was based; (3) *heuristics*, including rules-of-thumb for use in diagnosis. Of the three groups, the heuristics group was better in both familiar and unfamiliar situations. The theory group performed no better than did the no-story group.

Miller (1975) described research in which students receiving a traditional theoretical presentation were compared with students provided with a function- and action-oriented presentation. (A more complete description of this study may be found in the section on guidance in the use of context-specific knowledge.) Students with the theory-based course were slower, made more errors, and were less often successful in troubleshooting.

Van Matre and Steinemann (1966) and Steinemann, Harrigan, and Van Matre (1967) presented the results of an experimental training program in electronics for Navy personnel whose aptitude scores were too low for admission into the regular training program. The course of instruction in this program was altered to include less theory and more job-related information. On most dependent measures of troubleshooting performance, the experimental group was equal or superior to a control group of regular students completing the normal training course. These measures included overall performance, instructor and peer ratings of ability, and time required to troubleshoot. However, the experimental group scored lower on a test of system knowledge and indicated a desire for more theoretical instruction. In a subsequent follow-up study, in which graduates of the experimental training program were compared with a group of average trainees, more of the experimental graduates were successful in finding faults.

Williams and Whitmore (1959) conducted a longitudinal study of electronics technicians. Knowledge of theory was greatest immediately following their training program and was lowest when the follow-up test was given three years later. On the other hand, troubleshooting ability was *worst* immediately following training, and best at the time of the final follow-up test.

Foley (1977) presented the results of seven studies (including that of Williams and Whitmore), in which job performance had been compared with performance on theory tests and job knowledge tests. Correlations obtained ranged from 0.02 to 0.55, with a mean of 0.21. Correlations with job knowledge tests were slightly higher than with theory tests.

Summary. The results of these studies indicate that instruction in theoretical principles is not an effective way to produce good troubleshooters. It is interesting to note that

these results are quite consistent with reports from other domains such as process control (Brigham and Laios, 1975; Crossman and Cooke, 1974; Kragt and Landeweerd, 1974; Morris and Rouse, 1985) and mathematical problem solving (Mayer and Greeno, 1972; Mayer, Stiehl, and Greeno, 1975), in which explicit training in theories, fundamentals, or principles failed to enhance performance and sometimes actually degraded performance. Fundamental understanding has been empirically shown to be useful for answering theoretical questions but not for solving problems.

Opportunity for Practice

The essence of this approach is to provide the troubleshooter with opportunities to practice solving problems using the actual system or some form of simulation. As noted in the section on the role of experience, it has often been said that practice makes perfect. This approach is seldom used in isolation and is usually used in conjunction with some theoretical instruction. (In fact, all of the subjects in the studies summarized in this section had received such instruction prior to participating in the research.) We have included it as a separate category here because in some of the studies reviewed, the opportunity for practice was a primary goal of the development of the device or method investigated. As with the first approach, the development of an appropriate strategy may be left to the troubleshooter.

The opportunity for practice seems to have been the primary rationale behind the creation of the Generalized Maintenance Trainer Simulator (GMTS), now known as the Electronics Equipment Maintenance Trainer (EEMT). The EEMT is a computer-based interactive simulator that uses videodisc-based images of the system being simulated. The images depict what the troubleshooter would see if the actual system were examined. The troubleshooter solves problems by manipulating switches and controls via a touch-sensitive device and then observing the effect of actions upon equipment state. "Tests" are also performed as necessary, using simulated test equipment readings, until single faults are located.

The findings of the GMTS/EEMT studies may be summarized as follows. In the early studies, as students practiced with GMTS they became faster and made fewer replacements in subsequent GMTS problems. These trends may reflect a learning process that was taking place; however, no statistical tests were performed in these studies (Rigney, Towne, King, and Moran, 1978; Rigney, Towne, Moran, and Mishler, 1980). In a later study, the performance of students allowed to practice with either the actual equipment or GMTS only was compared (Towne, Munro, Johnson, and Lahey, 1983). All students had the same number of practice problems. When tested on actual equipment, there were no differences between the two groups in number of replacements or solution times.

Subsequent studies using EEMT (Cicchinelli, Keller, and Harmon, 1984) also reported improvements in troubleshooting performance. When EEMT was made available to students for extra practice, those students with access to EEMT demonstrated an 11% gain in troubleshooting performance on actual equipment. When students in another study solved the same number of problems either with EEMT or with operational equipment, there were no differences on a performance test. Those students who practiced on actual equipment were, however, rated more highly by laboratory instructors. In a follow-up investigation of students participating in this study, there were no differences between

training groups with regard to the need for later training.

Opportunity for practice was also an important feature in research by Johnson and Rouse (1982a, 1982b). Three groups of students in a maintenance training course solved simulated problems in either a context-free or context-specific environment, or watched videotaped demonstrations of troubleshooting on actual equipment. Subsequent performance in troubleshooting actual equipment was roughly equivalent for the three groups. (This research is reviewed in greater detail in the section discussing the effects of action-related feedback.)

A form of guided practice was described in a study from the area of process control. Duncan and Shepherd (1975), using a mock-up of a control room operating panel, simulated faults in a process plant by altering displays of state variables. Operator trainees then practiced diagnosing the faults via a "cumulative part" training technique, identifying those features that served to distinguish faults from each other. Duncan and Shepherd reported a general trend toward faster diagnosis with practice, but no statistical tests were performed.

Summary. Considering the results of these studies, it may be stated that practice in troubleshooting improves performance. In some cases (e.g., GMTS versus actual equipment), the opportunity for practice was found to be more important than the mode of practice. Of course, the extent to which this may be true depends on the characteristics of the simulation used. (See the later section on simulators versus actual equipment for an elaboration of this issue.)

As noted, opportunity for practice is seldom used in isolation as a training technique. Having the trainee "discover" requisite knowledge and skills would seem intuitively to be an inefficient and time-consuming process, particularly for large or complex systems. Opportunity for practice is

viewed as an essential part of a training program. For the full potential benefits of practice to be realized, however, complementary instruction should also be provided.

Guidance in the Use of Context-Specific Knowledge

A third approach focuses on helping the troubleshooter use his or her context-specific knowledge. Judging from the reports classified in this category, a typical assumption is that the troubleshooter possesses some knowledge about the system, such as the way the system functions. (This can be contrasted with knowledge of troubleshooting algorithms or procedures, which is discussed in a later section.) The goal of this approach is to create conditions in which the troubleshooter tries to apply this knowledge to problem solving, with or without explicit instructions to do so. For example, a troubleshooter might be told to generate hypotheses as to the cause of symptoms prior to beginning work.

Evidence suggests that encouraging troubleshooters to plan before acting can enhance their performance. In an experiment conducted by Moore et al. (1955), trainees were required to list the possible causes of failures prior to solving mock-up generator problems. They also identified critical tests of those hypotheses and proceeded to troubleshoot using the outline generated as a result of this planning process. Students required to proceed in this manner solved more problems than did a control group that was allowed to use any approach they wished.

Helping students to organize the information provided to them may influence their troubleshooting performance. Miller (1975) described an experimental training course for radar mechanics, in which an effort was made to relate instruction in system functioning to actions performed during troubleshooting. For example, system behavior was presented in terms of causal sequences rather than a more traditional left-to-right presen-

tation of schematics. Whenever possible, attempts were made to relate schematics to the actual equipment, often with the use of photographs of the system. Students were encouraged to organize the information they were given and to think of related activities (such as actions required to perform tests) as chunks rather than as isolated actions.

A control group received instruction in the theory upon which the system was based and a left-to-right presentation of schematics, with no extraordinary attempt to relate the information to actual equipment. Both groups had limited access to the actual radar for troubleshooting practice. The experimental group was faster in performing checks and adjustments, was more often successful in troubleshooting, made fewer errors in general, and scored better on quizzes.

Providing troubleshooters with guidance in how to analyze symptoms has also been shown to be helpful. Fattu and Mech (1953) manipulated the nature of information given to students prior to solving gear train problems. One group received only standard operating procedures. A second group was given an introduction to the gear train, including nomenclature and basic functioning, in addition to the standard operating procedures. A third group received all of this information plus instruction in symptom analysis. As a result of their training, the third group solved more problems than did the other groups. Interestingly, the speed with which the third group solved problems did not improve over time, whereas the other two groups became faster.

Perhaps the most ambitious attempt to provide guidance in the use of system knowledge has been the creation of SOPHIE (*SOPH*isticated *I*nstructional *E*nvironment). SOPHIE is an intelligent interactive computer-based instructional system used for teaching electronics troubleshooting. The authors of SOPHIE have been quite explicit in stating the rationale behind their work.

SOPHIE is designed with the goal of helping students to obtain a teleological understanding of their system and represents an attempt to provide an opportunity for students to apply their knowledge and "exercise their logical muscles."

Brown, Rubenstein, and Burton (1976) described two possible uses of SOPHIE. One is a team troubleshooting game, in which pairs of players seek to outwit each other by figuratively inserting faults into a simulated electronics system. The other involves observation of and interaction with an expert troubleshooter as it solves student-initiated problems. Analysis of verbal protocols taken from people interacting with SOPHIE in each of these scenarios indicates that people do indeed appear to call upon their system knowledge as expected. Response from users of SOPHIE has also been favorable. It is unfortunate that there is no transfer data available to indicate that forcing people to use system knowledge in this way does actually enable them to be better troubleshooters. However, the concept is intuitively appealing.

Summary. When one compares these results with those reported in the section on theoretical instruction, it becomes clear that, whereas theoretical instruction alone does not appear to be an effective approach to troubleshooting training, teaching people how to use the knowledge they have can lead to better performance. It should be noted that the studies in which positive effects were found involved guidance that was rather explicit: students were told to generate hypotheses, chunk information, and analyze symptoms in a prescribed way. This is different from providing an opportunity to use system knowledge and should not be interpreted as evidence that such an approach will produce better troubleshooters. The important question, whether exercising one's logical muscles enables one to troubleshoot more effectively, remains unanswered and should be investigated.

Guidance in the Use of Algorithms or Rules

This category of training approaches includes those that attempt to provide the troubleshooter with a particular strategy or at least constrain the set of strategies used. This is the largest category of the four discussed in this report, and it encompasses a wide range of studies. Typically, studies in this category attempted to constrain the troubleshooter's strategy in one of four ways.

First, some researchers were not explicit in telling the troubleshooter what should or should not be done, but provided an example of the "right" way to do things and observed troubleshooting behavior to see if this example was followed. Second, troubleshooters were sometimes supplied with feedback as to the acceptability of their actions, but the criteria for acceptable actions were not stated. A third approach was to tell the troubleshooter about appropriate algorithms or rules and observe him or her to determine whether or not the approach was followed. Finally, in some cases the task of troubleshooting was fully proceduralized. Although it would be more appropriate to call this approach "aiding" rather than "training," proceduralization is discussed here for completeness.

Provision of examples. One illustration of the provision of models has been noted in the discussion of SOPHIE and its capability to allow students to observe an expert troubleshooter in action. The expert troubleshooter solves problems according to an optimal strategy. In that discussion, the lack of transfer data was noted.

Access to an "expert" is also a salient feature of the Adaptive Computerized Training System (ACTS) (Crooks, Kuppin, and Freedy, 1977; Hopf-Weichel, Purcell, Freedy, and Lucaccini, 1979). Users of ACTS may troubleshoot a computer-based simulation of a power supply by entering commands to make tests, replace components, etc. Expert recommendations as to a course of action may be

obtained from a model based upon maximizing the expected value or utility of actions. Data from two experiments with ACTS were available.

In the first experiment, six college students received one of three experimental treatments. One group selected actions from a list of three alternatives supplied by the expert model and received feedback as to which of the alternatives would have been the expert's choice. A second group received only the expert's feedback after determining their own actions. Both of these groups had the opportunity to change their actions after receiving feedback from the expert. A third group did not have access to the expert at all. Expert aiding was available in two sessions and was withdrawn in the third session. The first two groups achieved lower-cost solutions to problems when the aiding was present, but there were no differences in the three groups during the third session when no aiding was available. This conclusion is based upon means only, as there were no statistical tests performed. Additionally, the test of transfer to an unaided situation was confounded by the fact that the problems solved during the third (unaided) session were identical to those solved in the first session.

The second experiment with ACTS involved three college students solving problems in two sessions. It was reported that the expert model converged with the performance of two subjects by the end of the second session. As with the first experiment, no statistical tests were performed, and there was no test of transfer to unaided situations, so the effectiveness of this technique as a training approach cannot be assessed.

There is limited evidence available, however, that provision of a model approach can lead to improved troubleshooting performance. Duncan (1971) created a mock troubleshooting task consisting of a chain of block components with various probabilities

of failure and provided college students with a decision tree aid based upon an optimal half-split approach. The students were instructed to troubleshoot according to the decision tree and to try to determine the rationale underlying the recommended decisions. The use of the aid led to improved performance for all subjects. However, as noted in an earlier section, the degree to which this improvement was retained in the absence of the aid was highly related to ability, as measured by pre-aiding performance.

Feedback about actions. In most of the studies reviewed, action feedback was in the form of *bookkeeping*, that is, identifying the feasible set of remaining alternatives given the results of tests already performed. As an illustration, consider research in which college students were given a set of symptoms and asked to identify the component common to those symptoms (Brooke, Duncan, and Cooper, 1980; Brooke, Duncan, and Marshall, 1978). For example, subjects were asked to discover which "factory" was discharging pollutants into the river, given symptoms such as "dead fish" and "bad smell." Problems were displayed on a CRT, and subjects were allowed to perform actions such as checking the color of the water at certain locations, etc., by entering commands at the terminal. After each action, feedback displayed at the screen's bottom indicated the set of alternatives remaining, given the results of that test.

Two experiments were performed using this approach. In the first experiment, subjects were presented with three types of problems: identification of (1) famous people, (2) random names, or (3) factories. One group received the feedback while solving the famous people and random names problems and then solved the factories problems without feedback. A second group solved the famous people and factories problems with feedback and transferred to random names

without feedback. Groups 3 and 4 served as control groups and received the same treatment as Groups 1 and 2, respectively, with the exception that no information about the feasible set of alternatives was ever provided. Surprisingly, there was no positive transfer for the first group when feedback was removed, but there was for the second.

The experimental procedure was essentially the same for the second experiment, with the exception that problems involving cities were substituted for the famous people problems. As a result, identification of the feasible set led to positive transfer for both experimental groups. These findings led Brooke et al. to conclude that feedback about the set of possible faults may produce positive transfer, but only if the feedback is provided in a variety of situations during training.

Aiding in the form of action-related feedback was also investigated in a series of experiments by Rouse and his colleagues. A full discussion of each experiment conducted would be rather lengthy and unnecessary for this paper, so the reader is referred to Rouse and Hunt (1984) for a detailed description of the 10 experiments reviewed. For present purposes, a summary of the general approach and major results will suffice.

Troubleshooting performance was investigated in the context of two experimental computer-based tasks. The first, Troubleshooting by Application of Structural Knowledge (TASK), is a context-free environment in which the troubleshooter is shown a pattern of system outputs in the form of zeros and ones and is given the problem of locating the faulty component by testing connections between components. Two versions of TASK have been used. TASK1 contains no feedback loops, and consists solely of AND gates. TASK2 contains both AND and OR gates, and includes feedback loops.

The second experimental task used is

FAULT (Framework for Aiding the Understanding of Logical Troubleshooting). FAULT is similar to TASK in that it consists of a network of components but, unlike TASK, contains a great deal of context. A number of systems have been simulated in the FAULT framework, including automobile engines and a variety of aircraft engines. The troubleshooter attempts to solve FAULT problems by entering commands to make tests, replace parts, etc.

Feedback or aiding in most of the TASK and FAULT research has consisted of identification of the set of possible faulty components in TASK1 problems. Several positive transfer effects have been noted as a result of aided practice on TASK1. For example, subjects provided with aiding during training on TASK1 made fewer tests to solution on subsequent unaided TASK1 problems; there was, however, an increase in time required during the first unaided problems. Interestingly, after practicing on aided TASK1, time to solve TASK2 problems was initially longer than for a control group that received no aiding during practice. However, time to solve TASK2 problems eventually decreased, and aided subjects became faster than those in the control group.

Aiding on TASK1 led to differences in the amount of information obtained per action when solving FAULT problems. These effects were also dependent on experience. Positive transfer effects were obtained for students in the fourth semester of an aircraft maintenance training course, whereas negative effects were obtained for first-semester trainees. Finally, aiding on TASK1 had a beneficial effect on the number of inefficient actions (compared with an optimal solution) made in solving FAULT problems. This effect was greater when transferring to problems in unfamiliar FAULT systems.

The effects of practice with aided TASK1 and FAULT upon troubleshooting of actual equipment were investigated in two experiments conducted by Johnson and Rouse (1982a, 1982b). Subjects were students enrolled in the last semester of an aircraft maintenance training course. Three approaches to training were compared in the first study. One group of subjects solved 60 aided TASK1 problems. A second group solved 35 FAULT problems, including problems with an automobile engine and two aircraft engines. A third group was given a reading assignment on troubleshooting and watched videotapes demonstrating the troubleshooting of three faults on actual equipment. Training effectiveness was evaluated by observing trainees as they solved five problems on actual equipment.

The results of this experiment were as follows. First, there were no differences between groups with regard to time to solve problems. Second, the performance of those students who watched the videotaped troubleshooting demonstrations was rated higher overall by instructors. Third, ratings of the quality of the sequences of tests made were comparable for all groups, with one exception. Three of the problems solved during the evaluation had been demonstrated in the videotaped lessons; students who had seen the videotapes achieved higher quality ratings on those problems.

Analysis of errors made by students while troubleshooting indicated that those students who practiced with FAULT made significantly more errors than did the videotape group in the use of test equipment, and that those who practiced with TASK1 made little use of test equipment at all. In light of these results, FAULT was modified to include an explanation of the use of test equipment, and the second study was conducted. In this experiment, a videotape group was compared to a group receiving practice on both aided

TASK1 and the modified FAULT. No significant differences between the two groups were observed.

Experiments conducted by Hunt (1981) and Johnson and Fath (1984) investigated the effects of another form of action-related feedback. In these studies, aiding was introduced into the FAULT environment. Whenever a test was made that was inappropriate in light of known symptoms or the results of previous tests, subjects received messages explaining the reasons why they should not have needed to make that test. These messages were explicit and highly context-specific. Hunt found that maintenance trainees provided with this error feedback made fewer inferential errors on subsequent FAULT problems and that this effect persisted regardless of the system simulated. In the experiment conducted by Johnson and Fath, performance of students trained using a FAULT-based simulation was compared with the performance of students trained with actual equipment. In all cases the performance of the FAULT-trained students was found to be equal or superior to the group using real equipment.

Whereas the approaches involving feedback about inferential errors and the set of remaining alternatives have been shown to have positive effects upon troubleshooting performance, supplying subjects with unexplained ratings about the quality of their actions has had undesirable results. Rouse, Rouse, and Pellegrino (1980) rated subjects' actions while solving TASK problems as being excellent, good, fair, or poor. Ratings were based upon the judged quality of heuristics that Rouse et al. felt could have been used to generate the actions. Subjects were given no information about the source of the ratings. Rating actions in this manner led to the solution of fewer problems and more tests made per problem.

Instruction in algorithms or rules. With the exception of one study reviewed, the algorithm of choice was a half-split approach, with the goal of minimizing the number of tests required to localize the source of a failure. This exception was a study by Glass (1967), in which students heard a series of taped lectures on "systematic troubleshooting," instructing them to use a tracing-back approach. As a result, students receiving lectures were more successful in troubleshooting actual equipment than were students who did not hear the lectures.

Goldbeck et al. (1957) conducted two studies in which subjects were instructed in the use of a half-split approach. The troubleshooting task employed was a simple simulation consisting of a network of block components and outputs of zeros and ones. In the first study, the independent variables were complexity of the network and the availability of instructions in the half-split approach. Goldbeck et al. reported the following effects of the half-split instructions. First, persons instructed in the use of a half-split approach made fewer tests in simple networks prior to locating the failure, but not when the networks were more complex. They also required more time to solve problems, and this difference increased with problem complexity. Finally, they appeared to be no better than the control group at identifying the set of feasible alternatives.

Differential effects of instructions were also investigated in the second study. In addition to a control group that received no information about the half-split approach, three groups received variations of half-split instructions. The "half-split" group received practice in identifying half-split tests, but no practice in identifying the set of feasible alternatives. The "deductive half-split" group received instruction in the concept of a half-split, plus practice with complex problems

and the opportunity to correct errors after feedback. The "deductive alternatives" group received half-split instructions plus a discussion of alternative (suboptimal) ways to eliminate components from further consideration.

Although there were no differences between groups in the number of replacements made, the deductive half-split group required fewer tests than did the other groups, and their first checks were more often in the feasible set of alternatives. In general, the performance of the deductive half-split group was superior to the performance of the experimental group in the first study. As an interesting note, the first checks of the half-split group were in the feasible set less often than were those of any other group.

Goldbeck et al. interpreted their results as follows. If the system is simple, then teaching troubleshooters about the half-split concept may enhance their performance. However, if the system is complex, additional instruction and practice in identifying the feasible set of alternatives may be required. As may be recalled from the discussion of this study in the section on individual differences, this need for elaboration and practice may be less for persons with high ability.

Brooke, Cooke, and Duncan (1983) also investigated the value of instruction in the half-split approach, using an experimental task similar to TASK developed by Rouse. There were two independent variables in their research: the availability of strategic instructions, and the availability of aiding. The instructions consisted of a discussion of the concepts of half-split and bracketing and a caution to make diagnoses only with sufficient information. Aiding involved providing feedback when tests made were redundant or diagnoses were premature.

Brooke et al. reported that subjects tended to make premature diagnoses if not provided instructions or aiding, and did not improve over time. Aiding alone was somewhat helpful in alleviating this problem, and instructions were initially useful. However, the beneficial effects of instructions on premature diagnosis deteriorated if aiding was not also available. This was not the case with test efficiency, where a general overall improvement due to instructions was noted. From these results, it was concluded that the instructions were generally more effective in influencing troubleshooting strategies than was the aiding, and that the efficiency of testing was more easily improved than were diagnostic errors.

Explicit instruction in heuristics rather than an algorithm was the approach employed by Shepherd et al. (1977), Marshall, Scanlon, Shepherd, and Duncan (1981), and Marshall, Duncan, and Baker (1981). The research by Shepherd et al. is described earlier, in which supplying process operator trainees with diagnostic rules was found to be more effective than providing them with theoretical instruction. In the experiments reported by Marshall and colleagues, greater effort was made to ensure that the trainees used the rules as instructed by controlling their access to system information. Trainees received information in one of two ways. Either information was displayed all at once, as on a conventional control room operating panel, or trainees had to request information as desired via a terminal keyboard.

By thus limiting the sequence in which information was accessed, it was possible to force the use of the diagnostic rules. The effectiveness of the method was evaluated by observing persons trained with each mode of information presentation as they diagnosed faults from a conventional unrestricted display. Those persons forced to use the diagnostic rules during training were more successful in making diagnoses.

Proceduralization. In the research just described, troubleshooters learned a list of rules, which they sought to apply when making diagnoses. Rules are also provided

when the task of troubleshooting is proceduralized, but the troubleshooter is not expected to memorize them. Rather, the procedures are always accessible, either on-line or in hard-copy form, and are retrieved as needed.

There is little doubt that supplying people with adequate procedures can have a positive effect on their troubleshooting performance. This has been demonstrated in several studies. For example, Potter and Thomas (1976) observed technicians as they performed electronics troubleshooting tasks and reported differences in number of correct solutions and time to solution as a function of the level of specificity of the job performance aid used. Smillie and Porta (1981) and Elliott (1966) noted improvements in the number of correct solutions, number of checks and unnecessary replacements, and solution time when proceduralized aids were used rather than more traditional approaches such as technical orders.

Most of the reports of the effects of procedures were written by Elliott (1965, 1966, 1967) and Elliott and Joyce (1968, 1971) and are discussed in conjunction with the effects of ability and experience. As a group, these studies may be viewed as indicating that proceduralization may be a very effective means of influencing troubleshooting performance, largely independent of ability or experience. To realize this, it is only necessary to recall the experiment in which proceduralization enabled high school students with no troubleshooting experience to find faults as accurately as Air Force technicians.

Summary. In light of the results presented in this section on guidance in the use of algorithms or rules, the following conclusions are offered. First, the limited evidence available suggests that providing troubleshooters with good examples can have a beneficial effect on their performance. However, learning from examples may be confined to persons with high ability. It may also be noted that subjects in the one study upon which this conclusion is based were explicitly instructed to learn from the examples provided. It seems likely that in the absence of this instruction less learning would occur.

Troubleshooting performance may be enhanced if action-related feedback is provided. If feedback is in the form of identifying the feasible set of alternatives, positive transfer effects may be noted only if this feedback is supplied in a variety of contexts during training or if the troubleshooter has some level of prior experience. Explicit feedback about inferential errors has also been shown to improve performance, but unexplained ratings about the quality of actions have produced negative results.

Instruction in algorithms has been found to be effective if (1) the algorithm is simple (e.g., tracing back), or (2) the system is simple. If the use of a half-split approach is desired and the system is not simple, then it may be necessary to provide extended instruction and opportunity for practice or to select troubleshooters with high ability. In the one study in which they were compared, instruction in the use of an algorithm was found to be more effective in improving test efficiency than was the provision of feedback.

Compared with theoretical instruction, the provision of heuristics can lead to improved troubleshooting performance. Greater improvement is realized if the use of the heuristics during training can be forced.

Finally, positive effects of procedures are possible, even with troubleshooters deficient in ability or experience. These effects depend to some extent upon the form and specificity of the procedures. Within reason, as procedures become more explicit, less ability and experience are needed for comparable performance.

Simulators versus Actual Equipment

A number of the studies reviewed in this report employed some form of simulation in

their research. Care must be exercised in generalizing the results of such research to real equipment performance because of differences in the nature of the simulations. There have been several instances reported in which performance using a simulator differed from performance using actual equipment. Because simulators are often employed in training, it is important to be aware of such differences. Due to their implications for training programs, studies are discussed here that compared performance on simulators with performance on actual equipment.

Standlee and Bilinski (1966) tested the troubleshooting performance of 114 data systems technicians with both a paper-and-pencil test and actual equipment. Although no statistical tests were presented, Standlee and Bilinski reported that ratings of performance on the two tests could lead one to reach opposite conclusions. Ratings of performance with the paper-and-pencil simulation were generally low, whereas performance using actual equipment was rated higher.

Similar results were reported by Steineman (1966). Student technicians solved identical faults using either a paper-and-pencil diagram or a hardware simulation of actual equipment. Most of the correlations between performance on the two simulations were negative. More replacements were made with the paper-and-pencil simulation, and use of the hardware simulation was associated with more wrong readings and rechecks.

Low correlations between measures of performance on simulated or actual equipment were noted by Shriver and Foley (1974) and Mallory and Elliott (1978). Both of these studies compared performance on a photo-based simulation with that on electronics equipment. Mallory and Elliott noted correlations between performance measures such as speed, accuracy, and number of steps, ranging from 0.35 to 0.58. Shriver and Foley reported higher correlations (ranging from 0.53 to 0.87) dependent upon the "level of penetration" of the troubleshooting task. As performance of the actual task required greater use of tools and test equipment (which was not possible with their simulation), then there was less of a relationship between performance measures on simulated and actual equipment.

Elliott and Joyce (1968) noted a relationship between aptitude and performance of a paper-and-pencil troubleshooting task but failed to find a similar relationship when the task involved was troubleshooting of actual equipment. Students with high aptitude were found to be more accurate than were those of medium aptitude in troubleshooting a paper-and-pencil simulation, but no differences were found in their troubleshooting of actual equipment. The explanation provided was similar to that offered by Shriver and Foley, citing differences in skills required to perform the two tasks.

Although differences in performance using simulators or actual equipment have been noted, those studies in which transfer from simulators to actual equipment was evaluated reported few or no differences in transfer (Johnson and Fath, 1984; Johnson and Rouse, 1982b; McDonald et al., 1983; Towne et al., 1983; Cicchinelli et al., 1984). In each of these studies, the opportunity to practice on the simulation was only part of a training program; often, practice on actual equipment was also provided. Therefore, it is difficult to assess differences that might have been present if only practice on the simulations had been allowed. What may be said is that in each of these training programs students allowed to practice on the simulation and students practicing only on real equipment appeared to acquire equivalent troubleshooting skills.

Summary. Three statements may be made in view of the research in which differences in performance with simulators and actual equipment were found. First, the relationship between troubleshooting performance and characteristics such as general abilities or aptitude is weaker as the range of required abilities increases. Stronger relationships may be found with simple simulations because performance may depend on a few skills. Second, performance on a simulation will be related to troubleshooting of actual equipment to the extent that the same skills are required. Some simulations only allow the troubleshooter to practice a strategy. If the student is not allowed to practice making tests and repairing or replacing components, then performance on the simulator may not be highly related to performance on actual equipment. Finally, these results underscore the need to evaluate transfer of training in the context of actual equipment.

CONCLUSIONS

In the introduction, we stated that three abilities are necessary for success in troubleshooting. These include: (1) the ability to repair or replace components, (2) the ability to perform tests, and (3) the ability to employ a strategy in attacking the problem. Because the third of these abilities poses such a conceptual challenge to instructors, and due to the nature of available literature, the focus here has been on the use of strategies. However, it is necessary to reemphasize the importance of the first two abilities as well. Teaching persons to repair/replace components and to make tests should be included in a training program, or care should be taken to ensure that these skills are acquired elsewhere. The importance of this statement is underscored by considerable anecdotal reports by the military that their technicians do not know how to use test equipment.

It was also noted in the introduction that the appropriateness of any strategy depends greatly upon performance criteria and other contingencies. This is an issue that is not dealt with explicitly to any great extent in training programs, possibly because the demands on graduates of a training program may differ widely across individuals. For example, the aircraft mechanic who goes to work for a major airline may be expected to minimize down time; the mechanic at a small private airport might be more concerned with the cost of repair. Similar differences may be associated with line versus depot maintenance.

The performance criteria of a particular job may also be expected to change, depending on circumstances. For example, the demands on military maintenance personnel might be expected to change dramatically in the event of a war. Thus, it may be worthwhile to investigate the human's ability to change his or her strategy dependent upon conditions, and perhaps to examine alternative ways of training troubleshooters to take such contingencies into consideration.

Although it is not entirely feasible to offer specific advice as to what strategies, if any, should be explicitly taught to troubleshooters, some consistent themes do emerge as a result of this examination of the research results available. Accordingly, we will attempt to be as definitive as possible with regard to what is known about troubleshooting. In most cases, the following statements are based upon the empirical evidence reported here; exceptions to this will be noted.

It may be stated with a fair amount of certainty that humans are not good at making probabilistic judgments and generally do not make very good use of such information. This was found in studies dealing specifically with troubleshooting and is consistent with a sizable body of literature in the area of human

judgment and decision making. Subject-matter experts exhibit the same kinds of error in probabilistic judgments as do novices, and merely informing people that their judgments are subject to such biases apparently has little impact. The only people who have been found to make relatively bias-free judgments of probabilities are those who are experts at making such judgments (e.g., weather forecasters).

The lesson to be learned from this is that although troubleshooters may base their decisions on qualitative perceptions of the likelihood of certain events, they should not be expected to make precise judgments about probabilities and should not be expected to optimize performance based on such probabilities. If it can be determined that it is absolutely necessary to take probabilistic information into account, then provision of some kind of aid should be considered. Otherwise, reliance on this type of information should be avoided.

Human troubleshooting performance has been found to degrade as systems increase in size or complexity, and if time constraints are imposed. If the system involved is large or complex, and/or if time is limited, then one or more of the following approaches should be considered: (1) require a relatively simple strategy; (2) provide more instruction and practice in applying the instruction; (3) select troubleshooters with higher ability; (4) provide some kind of performance aid, such as "bookkeeping" or procedures. There are obviously trade-offs involved in adopting any of these approaches, and the choice should depend upon such contingencies as the population from which troubleshooters may be drawn, the resources that may be allocated to each of these, and the extent to which each approach may be expected to lead to acceptable performance.

Evidence suggests that as instruction to troubleshooters is made more explicit, their behavior will probably be affected in the manner desired. Generally, if the troubleshooter is left to discover the best strategy for a given situation, this discovery will not occur. This interpretation is consistent with virtually all of the research reviewed, although perhaps the best illustration of this is the overall ineffectiveness of theoretical instruction in enabling persons to be good troubleshooters. Granted, if the trainees involved have high ability and/or are highly motivated, they may be able to develop an appropriate strategy given such instruction. In general, however, if the leap from instruction to action is too great, that leap will not be made successfully.

From this perspective, the most effective means of ensuring that the troubleshooter will successfully employ an appropriate strategy is to proceduralize the task. Positive effects with procedures were noted in each study in which proceduralization was used, even when troubleshooters had limited experience or moderate ability. However, we realize that there are important limitations to this approach. Procedures are not easily developed, and they are highly system-specific. In hard-copy form, they may be cumbersome and space consuming, and total reliance on a procedures manual implies that little could be done if no manual were on hand. Therefore, explicit instruction in some algorithm or in diagnostic heuristics, either of which would have greater generality and would result in less dependence on a manual, seems to be a desirable alternative to proceduralization.

It is possible to imagine that some instructors would prefer to have troubleshooters rely on their knowledge of the system rather than on an algorithm or on rules. Even if this were to be the focus of training, a case may be made for explicit action-related instruction. In studies in which troubleshooters were given specific guidance

in how to apply their knowledge (e.g., organize information into chunks or generate hypotheses and plan an appropriate course of action prior to beginning work), the provision of this guidance led to better performance.

This call for explicitness is contrary to the approach in which the trainee is not told what to do but rather is placed in a situation that is intended to force the use of system-relevant knowledge in order to determine a course of action. However, limited support for this latter approach can be found in research indicating that forcing people (as opposed to providing them with the opportunity) to use the information they have can lead to improved performance. Most of the evidence is directly relevant to the use of an algorithm or heuristics rather than theoretical knowledge, but the results of one study and aspects of another do suggest that this may also be the case with knowledge of the system.

Perhaps the current state of knowledge may be summarized as follows. Either troubleshooters should be explicitly instructed in how to approach problems or they should be forced to use their knowledge of the system explicitly in deciding what to do. Unfortunately, a definitive statement as to which of these is the better approach cannot be made because of a lack of data. The latter has not been evaluated in a transfer study, and the two approaches have not been compared with each other experimentally.

It seems feasible that a combination of these approaches, taking advantage of the possible benefits of each, could be the most effective means of teaching troubleshooting. The use of an algorithm or heuristics could impose less cognitive load on the troubleshooter and could be successful even when knowledge of the system is limited. On the other hand, a knowledge of the functioning of the system could enable the troubleshooter to focus on a portion of the total system and, in effect, reduce the size and complexity of the system under consideration. This in turn could make it possible for the troubleshooter to use an algorithm such as a half-split approach more effectively.

Admittedly, this is conjecture and is not based upon empirical evidence, but it does appear to be reasonable. The extent to which requiring people to use their theoretical knowledge can enable them to troubleshoot more effectively is largely unknown and should be evaluated experimentally. Further evidence is also needed to determine the appropriate degree of emphasis on algorithmic and theoretical approaches.

As a final observation, we have noted a characteristic of the literature reviewed. Several of the studies summarized here were conducted some time ago and typically used low-tech approaches to experimentation, such as paper-and-pencil simulations. However, the goal of these experiments was to learn something about human troubleshooting behavior, and transfer to actual equipment was often investigated. Generally, the data generated by these studies are useful today.

In contrast, several more recent reports have discussed high-tech approaches, with sophisticated computer-based simulations, elaborate graphics, "expert" models, etc. Yet, accompanying this trend toward greater use of technology, there seems to have been a shift in emphasis that avoided, either purposefully or incidentally, an evaluation of transfer of training. All too often, recent "experiments" have been demonstrations rather than evaluations. In light of the large number of questions remaining, this is an unfortunate trend. Verification of the feasibility of an idea is a necessary step, but it should not be viewed as the final step. Research should retain as its primary goal the evaluation of transfer to real-life situations.

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