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ABSTRACT

Electronic troubleshooting expertise was explored in the three contexts (design, production, and repair) that reflect distinct problem solving task environments. The purpose of the effort was to provide a more precise definition of the boundaries of expertise in electronics troubleshooting and the relationship of context to the development of troubleshooting instruction. Actual troubleshooting performance was studied in contextually representative tasks. Two subjects (engineers and technicians) were selected from each of the following areas: (1) design engineering; (2) production testing; and (3) customer service or field service. Troubleshooting on an aircraft electrical system simulator board with design, production, or normal wear flaws was studied. Beyond knowing where to start in the process, actual troubleshooting process differences were few. Generally, all subjects were able to perform in a manner consistent with their expertise, and there appeared to be little overall difference in the ability of the troubleshooters to generate and evaluate hypotheses, acquire and interpret information, or select an appropriate problem space beyond the contextual reference. Difficulties were generally overcome through self-correction and continued data gathering. Subjects from all groups were able to demonstrate high levels of skill on these problems that were representative of typical job contexts. Implications for instruction in troubleshooting are explored. Five figures and five tables illustrate the discussion. (Author/SLD)

CONTEXT AND EXPERTISE: THE CASE OF ELECTRONIC TROUBLESHOOTING

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Abstract

The purpose of this study was to explore electronic troubleshooting expertise in three contexts (design, production, and repair) that reflect distinct problem solving task environments, in an effort to provide a more precise definition of the boundaries of expertise in electronics troubleshooting and the relationship of context to the development of troubleshooting instruction. Based on the cognitive science approach to the study of expertise, the investigation explored actual troubleshooting performance in contextually representative tasks. Although broad generalizations are limited due to sample size, important implications for the study of electronics troubleshooting expertise were discovered.

The contexts under study represented three distinct task environments, defined by job related responsibilities. It appeared that beyond knowing where to start in the process, actual troubleshooting process differences were few. Generally, all subjects were able to perform in a manner consistent with expertise as defined by solving the problem representative of their respective contexts. There appeared to be little overall difference in the ability of the troubleshooters to generate and evaluate hypotheses, acquire and interpret information, or select an appropriate problem spaces beyond the contextual reference. Difficulties with interpretation of information or hypothesis evaluation were generally overcome through self correction and continued data gathering. In essence subjects from all groups were able to demonstrate high levels of skill associated with expertise in electronics troubleshooting within problems representative of their typical job contexts and experience.

Context and Expertise: The Case of Electronic Troubleshooting

The cognitive science approach to the study of expertise holds promise for improved troubleshooting instruction (Bedard, & Frederiksen, 1992; Foshay, 1989; Fredericksen, 1984; Johnson, 1987; Johnson, Flesher, Ferej, & Jehng, 1992; Keller, 1985). However, research in electronic troubleshooting has focused primarily on maintenance scenarios (Johnson, 1989; Keller, 1985; Lesgold et al., 1986; Rasmussen & Jensen, 1974), or has been guided by singular experts (Bedard & Frederiksen, 1992; White & Frederiksen, 1987). The organization of domain knowledge and its typical application appears to depend upon the tasks that experts routinely perform (Smith, 1990). In electronics troubleshooting, Rasmussen and Jensen (1974) reported differences in problem solving behavior between design engineers and maintenance technicians. The problem solving goal of maintenance technicians is the discovery of a fault in a system that has been working properly. Design engineers, however, are more likely to consider the theoretical constructs and basic conceptual operation of a faulty system. The purpose of this study was to explore electronic troubleshooting expertise in three typical problem solving contexts (design, production, and repair) in an effort to provide a more precise definition of the boundaries of expertise in electronics troubleshooting and the relationship of contextual emphasis to the development of troubleshooting instruction.

The Role of Context

Context is consistently recognized as an important element in problem solving research (Ericsson & Smith, 1991; Johnson, 1988; Keller, 1985; Stepich, 1991). However, the focus of expertise research has been on problem solving processes and theories of potential cognitive structure and function, and not on the effects of external environments or stimuli (Tennyson, 1990). The role of context is implicit in the cognitive science approach to the study of expertise. A problem solver brings an internal set of values, knowledge, and skill to each environmentally bound problem situation. In effect an internal context absorbs and interacts with the external context resulting in observable behavior. The term domain itself is certainly a reflection of a specific environmental situation. The discovery of domain-specific pattern recognition in chess by Chase and Simon (1973), and the numerous validating studies in diverse domains, may in fact imply that superior performance is tied to a contextual reference, or structure. The chess board and the rules of the game may represent a context for problem solving that cues appropriate domain-related knowledge including a set of specific global and move related goals, rule structures, and past memory of effective strategies and styles of previous opponents.

Cognitive competence is developed and demonstrated in specific external contexts. This contextual structure determines the domain of relevance (Hagendorf, 1990). Studies of expert performance have repeatedly found superior performance to be linked to specific domains, or in effect, situations (Chase and Simon, 1973; Chi, Feltovich, & Glaser, 1981; Egan & Schwartz, 1979). Context influences the perception and methods used to solve problems. Initially, process is linked to a particular domain, acquired in response to an environmental challenge faced by the developing organism. Context directs attention to certain problems, and particular aspects within problems, playing a crucial role in cognition. Context also leads to the selection of resources in the problem solving process (Ceci & Nightingale, 1990).

Context has been found to exhibit important effects in many cognitive domains. These include visual perception (Ceci & Nightengale, 1990; Neisser, 1976) speech recognition (Massaro & Cohen, 1991) and semantic similarity (Miller & Charles, 1991). Lawrence (1988) studied the differences between novices and experts in judicial decision making. The expert judges were found to have specific "frames of reference" concerning case types which guided their decision making process. These frames are representational schemas that describe procedural operations in combination with preexistent perspectives. These perspectives appear to influence the objective or goal assigned by the judges to each type of case.

In a study of expertise in classical genetics, Smith (1990) concluded that there can be more than one kind of expertise within a discipline based on the typical manner in which experts apply knowledge in response to specific task demands. Three groups, biology faculty members, genetic counselors, and undergraduate college students were given genetics problems to solve and were instructed to organize the problems by how they would be solved and then to circle the key words that supported the organization. Although faculty and counselors were both found to be successful at solving the problems the faculty members tended to organize the problems based on concepts while both the counselors and students focused on the problem knowns and unknowns. This difference in knowledge organization among the two expert groups appears to reflect the different purposes for which that knowledge is applied.

Knowledge organization may also be different for electronics troubleshooting experts based on typical applications. Rasmussen and Jensen (1974) report that their collected protocols clearly indicate that maintenance technicians define their task as the search for a fault in a system which has previously operated properly. The designer, however, defines the task as understanding the basic function of the system, comparing conceptualizations to observation. Johnson (1987) discovered differences in expert behavior in an investigation of novice and expert troubleshooting. In that study two of the experts took considerably longer to solve a problem than did the novices because they got sidetracked by what they perceived as a design flaw. It seems plausible that the experts' slower performance may have been a result of a design oriented frame of reference.

Contextual problem solving continuum. In order to study the relationship of context in problem solving, a method must be established to define that element (Tennyson, 1992). In most research on expertise, or problem solving, the context has been implied by the rarely defined "domain" reference of the study (i.e., technical troubleshooting, physics problem solving, or medical diagnosis). Certainly in any of these cases, the generalizability of results must be limited by the goal structure imposed by the research design, the specific task set, and the individuals selected to participate in the study.

Two common attributes of problem solving behavior are found extensively in the literature; that problem solving is goal based (Anderson, 1987; Bereiter, 1990; Cooke, 1988; Garner, 1990; Glaser, 1985; Hagendorf, 1990; Johnson 1988; Simon, 1981; Tennyson, 1992) and problem solving is reflective of the environment in which it occurs (Bereiter, 1990, Simon, 1981, Garner, 1990; Johnson, 1988; Tennyson, 1992; Thomas & Litowitz, 1986). A model that represents the contextual element of a problem solving activity must therefore be based on these two elements.

Insert Figure 1 about here

Any effort to determine context free universal problem definitions based on characteristic attributes beyond physical or relational concepts are dependent upon the problem solver and contextual presentation. A system related definitional approach removes the inherently individual response to the amount of problem structure and definition. Accordingly, the problem of developing a framework for contextual evaluation has two additional requirements; the need to allow for completely individual responses and situations, and a definition based on physical or externally related concepts. Through an extension of the product/process life cycle paradigm (Collins & Devanna, 1990; Hayes, Wheelwright & Clark, 1988) a model was developed based on the complete life cycle of a single process or product from initial concept through discardment. This model, called the Contextual Problem Solving Continuum (see Figure 1) has three discrete stages (a) design or development, (b) implementation or production, and (c) maintenance or repair. Each phase has a distinct goal related structure. Problems in the design phase are novel presentations requiring the development of new knowledge and structure. Problems in the implementation phase require application of a known process or production of a viable design. Problems in the maintenance phase require the continuation of a specified standard, through adherence to a conceptual structure, or pre-determined physical condition. The individual relevance of this model is a function of environment and goal structure. The domain frame provides the environment (i.e., electronics, physics, or medicine). The individual's current problem solving goal determines the overall relationship of that person to a phase in the model (i.e., repair a previously working generator set, build a structure from blueprints, or design an electronic amplifier with unity gain).

Technical Troubleshooting Model

Through a synthesis of research studies, Johnson (1989) developed a Technical Troubleshooting Model that reflects the cognitive process flow of an individual engaged in troubleshooting a technical problem. The model is divided into two main phases (a) hypothesis generation and (b) hypothesis evaluation. In phase one the problem solver acquires information from internal or external sources that can be used to support a representation of the problem. Following the creation of this representation one or more hypotheses are developed that may account for the fault. In phase two, the problem solver evaluates a hypothesis that was generated in phase one and attempts to confirm or dis-confirm the potential cause of failure (Johnson, 1989).

In the first phase of the Technical Troubleshooting Model, the troubleshooter attempts to identify possible faults through a series of information acquisition efforts. These efforts enable the troubleshooter to develop a mental representation of the potential area in which the fault could exist called a problem space. The troubleshooter may obtain information from both internal and external sources. The internal sources available to the troubleshooter include declarative and procedural knowledge stored in the individual's long term memory (Johnson, 1989). Tennyson (1990) adds contextual knowledge which includes embedded situational criteria governing selection of appropriate knowledge structures. External information acquisition sources include job aids, technical support, technical evaluation utilizing test procedures or operational adjustments, and sensory evaluation through visual, tactile, auditory, and olfactory inspection (Johnson, 1989). These sources comprise a "toolbox" of available support for the troubleshooter. The quality of this toolbox will be dependent upon the resources available and the declarative and procedural knowledge bases of the troubleshooter. Keller (1985) notes that in realistic situations a troubleshooter may only have a sub-set of these resources available or in working order.

The second phase of the Technical Troubleshooting model involves the evaluation of a generated hypothesis. This process involves obtaining additional information to support a decision to either accept or reject the proposed hypothesis (Frederiksen, 1984). During this phase the troubleshooter determines if the potential fault is the true fault, and if able to make such a determination can then repair the problem. Troubleshooting is often a cyclic process, with each level representing a closer approximation of the actual fault (White & Frederiksen, 1987; Rasmussen & Jensen, 1974). If the fault is not identified in this phase, then the troubleshooter repeats the process of hypothesis generation (Johnson, 1989).

The process of troubleshooting requires an integrated ability to collect, process, and evaluate external and internal information. A correct fault solution may be obtained after many instances of incorrect hypothesis evaluation, or information interpretation. Conversely an incorrect judgment may result from a single failure to correctly interpret acquired information or evaluate generated hypothesis. This implies that an important element in the process is the ability to continue the cycle of processes represented in the Technical Troubleshooting Model, and to verify proposed solutions (Johnson et al., 1992).

Method

The purpose of this investigation was to compare technical troubleshooting performance in the three context areas. The investigation examined actual troubleshooting behavior on a set of contextually representative tasks. Data to support the investigation was primarily in the form of verbal protocols collected during the troubleshooting activity. The protocol data was supported by researcher observations and interviews conducted immediately following that activity. Additionally, graphic representations of each subject's area of responsibility, area of expertise, and problem space representations for the troubleshooting task were collected using the Contextual Problem Solving Continuum as a guide.

Subjects

The subjects selected for this study were professional engineers and technicians employed at Frasca International, Incorporated. Frasca is a manufacturer of a full line of state of the art aircraft flight simulators and radio products. Design, manufacturing, and customer service activities are housed in a single facility in Urbana, Illinois. Two subjects were selected from each of the following areas: (a) design engineering, (b) production testing, and (c) customer or field service, based on supervisor nomination.

Apparatus

The equipment used for this investigation was an aircraft electrical system simulator board designed to provide realistic troubleshooting experiences and practical examinations at the Institute of Aviation at the University of Illinois at Urbana-Champaign. The selected system, Electrical Systems Simulator Board B, contained ten specific discrete subsystems which represent realistic aircraft electrical systems. Components included circuit breakers, switches, relays, terminal strips, conductors, and major functional system components such as a rotating beacon, power inverter, landing lights, control motors, and a fuel pump.

Task selection

The process of task selection for this investigation was based on specific criteria to ensure a representation of specific populations of tasks. Task selection was also limited to problems that were not likely to result in immediate solution based on experience or cursory observation. Additionally, each problem was inserted so that it could be specifically identified. A pilot test of the entire fault set was accomplished prior to data collection. Three faults were inserted which represented a range of contextual relevance. The first fault was a concealed piece of transparent tape covering the point contact of the power path to the lamps within the rotating beacon. The second fault was a mis-wired microswitch in the down Gear Indicator circuit. The final fault was an incorrectly rated circuit breaker in the Inverter circuit and the circuit breakers value was altered on the schematic. The under-rated circuit breaker was a design flaw. The mis-wired microswitch simulated a production error, and the beacon contact simulated normal wear during operation, a repair fault.

Data analysis

The framework provided by the Technical Troubleshooting Model resulted in four linked reductionary levels of troubleshooting protocol analysis: (a) global performance, (b) fault isolation scenarios, (c) hypothesis generation/evaluation episodes, and (d) information acquisition/interpretation efforts. Following the coding and segmenting of verbal protocols (Ericsson & Simon, 1984) the protocols were divided into separate problem scenarios and general search areas not related to the three tasks. These data formed the basis for Global Performance Matrices (See Figure 2) that included the sequence of activities, subsystems examined, time devoted to each activity, information acquisition efforts within the activity, results of the activity, and researcher comments for clarification. Following the division of the protocols into general and fault specific sequences the fault scenarios were further divided into episodic events and plotted on an Episodic Performance Matrix (see Figure 3). An episode is defined as a complete pass through the Technical Troubleshooting Model (Johnson, 1987, 1989). Each episode consisted of (a) the selection of at least one potential hypothesis, (b) the acquisition of information for the purpose of evaluating the hypothesis, (c) the interpretation of the acquired information for the purpose of evaluating the hypothesis, and (d) a decision to accept or reject the hypothesis.

Insert Figures 2 and 3 about here

All sensory, test equipment based, or physically manipulative information acquisition efforts were analyzed for type, interpretation, self-correction of errors in interpretation, and redundancy. Fault specific efforts were plotted on functional circuit maps for each problem representing the order and problem space relevance of those efforts (see Figure 4). Two additional analyses were accomplished. First, specific subject fault activities for each task were represented in Episodic Performance Profile Graphs (See Figure 5). These graphs indicate interpretation of hypotheses, sequence and level of hypotheses, and problem space relationship of each hypothesis as well as the resultant solution related conclusions. Second, subject strategies for each fault scenario were placed in table form. The episodic matrices, categorical analyses, graphic representations, and strategy tables were compared and analyzed for commonalties and differences between subjects and for relationships to group and individual performance.

Insert Figures 4 and 5 about here

During the troubleshooting task, additional observation data was recorded by the researcher as well as the time devoted to each scenario. Observation data provided a source of clarification for the verbal protocol data, and a guide for recounting the activity (Cooke, 1988; Rasmussen & Jensen, 1974). An in-depth interview was conducted immediately after the troubleshooting performance task. The interview data was used to support and clarify the other data sources and generate specific contextual goal structures and problem representation relationships. Near the end of the interview each subject was asked to place a circle around their position at Frasca on the Contextual Problem Solving Continuum for electronics troubleshooting. On a second graph they were instructed to place the circle around the area they were an expert in, or felt the most competent. On a third graph they were asked to place the origination of the faults encountered during the troubleshooting performance activity as a representation of the global problem space associated by the subject with each specific fault. This data was compared by subject relative to group membership, reported expertise, and problem solution.

Results

The contexts under study represented three distinct task environments, defined by job related responsibilities. It appeared that beyond knowing where to start in the process, actual troubleshooting process differences were few. Generally, all subjects were able to perform in a manner consistent with expertise as defined by solving the problem representative of their respective contexts. There appeared to be little overall difference in the ability of the troubleshooters to generate and evaluate hypotheses, acquire and interpret information, or select an appropriate problem spaces beyond the contextual reference. Difficulties with interpretation of information or hypothesis evaluation were generally overcome through self correction and continued data gathering. In essence subjects from all groups were able to demonstrate high levels of skill associated with expertise in electronics troubleshooting within problems representative of their typical job contexts and experience.

Problem Solutions

Correct solutions occurred in nine of eighteen potential scenarios (see Table 1). All correct solutions were in reported areas of expertise, and two-thirds of the incorrect or inconclusive solutions were outside of subjects reported contexts of expertise. When asked to represent their areas of expertise on the Contextual Problem Solving Continuum only two subjects indicated expertise beyond their specific positions. Subject R1 who had worked in production prior to field service (repair) claimed a dual expertise in those areas, and subject D2 included the entire range of contexts in his response. During the structured interview subjects were again asked to indicate what additional areas they could work in, interview responses and graphic representations are summarized in Table 2.

Insert Tables 1 and 2 about here

There were traces of context effects evident in the subject's troubleshooting performance. The design problem was the clearest example. The two design subjects were the only individuals able to solve the design fault. Even when the other subjects had acquired the current ratings from both the Inverter and circuit breaker, they failed to consider the circuit's design. It is unlikely that the other subjects did not have the knowledge necessary to solve the problem as it did not require circuit analysis, formula manipulation, or theoretical abstraction, only a simple comparison of the two component values. It appeared that the other subjects relied on an inappropriate "frame of reference" or initial problem representation that they did not question.

The production group members only arrived at one correct solution, to the production problem. That area appeared to be common to the other groups in reported expertise. This may have been due to both previous experience in that context, and some degree of common activity associated with production tasks. Both designers reported checking wiring in prototypes as common design activities while repair personnel had to verify installations or component replacements. One production subject did not recognize the problem. This appeared to be due to a transfer of technique from his routine activities that did not include obvious symptomatic conditions. That subject worked on radio units and relied on oscilloscope tests to provide a "window" for circuit symptoms. Additionally, that subject appeared to be completely dependent on the schematic, and in fact stated that without a schematic he could not troubleshoot. A design subject also failed to solve the production fault, concluding that the Gear Indicator instrument had failed.

The repair subjects were able to solve both the production and repair problems, although they reported previous experience in both contexts. A design group member was the only other subject able to solve the repair fault. He also reported experience in field service activities. Two subjects, one design and one production, failed to pursue a maintenance orientation to the level necessary to effect a repair. Both subjects, although in a maintenance frame, would have replaced an entire unit for an insignificant internal fault.

Subjects with multiple context experience appeared to have little difficulty in solving problems from different contexts. Subject D1, the only subject able to solve all three faults, stated that he would have been more efficient on the design problem but initially he "wasn't in my design mode." This was the only direct reference to changing frames of reference during the troubleshooting activity. The awareness of the appropriate problem representation allowed the subject to "shift" to a relevant problem space and consider a related set of potential hypotheses.

Hypothesis Generation and Evaluation

Global hypothesis generation and evaluation data for each subject is presented in Table 3. The evaluation of hypotheses resulted in three outcomes (a) correct interpretations (b) incorrect interpretations, and (c) incomplete interpretations, or failure to complete the evaluation due to abandoning the hypothesis or reaching an impasse during the process. With the exception of Subject D1 who correctly solved every fault, and Subject P2 who did not solve any faults, a difference can be observed between hypothesis evaluation within correct solutions and overall evaluation efforts. Generally little difference can be attributed to group membership for the ability to evaluate hypotheses given the demonstrated evaluation accuracy within correct solutions. Subjects demonstrated a high level of correct hypotheses evaluation within the problems they correctly solved, consistently exhibiting characteristics associated with expertise for context representative problems.

Insert Table 3 about here

Information Acquisition and Interpretation

Two subjects (P1 and R2) correctly interpreted all of the information they acquired within the problems they solved correctly (see Table 4). When adjusted for self-correction of interpretation mistakes, however, all subjects achieved completely correct interpretations for the problems they successfully solved. All subjects, regardless of group membership, were capable of interpreting the information sought, particularly within problems representative of their contextual focus. Total correct interpretations for all problems attempted ranged from 75% for Subject P2, to 100% for both subjects D1 and D2. With the exception of Subject P2, all subjects attained a general interpretation rate, after self-corrections, of over 90%.

Insert Table 4 about here

Problem Space Representations

The range of acquisition efforts that were conducted in the appropriate subsystem problem space does not appear to reflect contextual group membership (see Table 4). This problem space does not reflect the depth of context within the problem space, but instead only the likelihood of fault potential within the component set. The range of .50 to .81 for all problems, or the correct solution range of .40 to .93, is more reflective of the problem type than subjects' general ability. The schematic diagram for Board B did not include detailed information concerning voltage paths, or internal operation for all circuits. The subjects had no previous experience with the system, and therefore often had to learn the circuitry while diagnosing the faults.

An overall indication of problem space depth can be developed from the subjects' graphic representations on the Contextual Problem Solving Continuums. Subjects were asked to place each problem in an appropriate range, representing an overall problem space characterization. Without exception each one of the correct component or device level solutions (n=11) were plotted in the correct corresponding area on the Contextual Problem Solving Continuums. Four of the six incorrect, or inconclusive solutions were placed in an incorrect area and two were appropriately placed. The solutions that were placed outside of the context problem space are indicative of the use of an inappropriate reference frame. The representations demonstrate that the subjects recognized the problems as characteristic of the specific contextual areas, and that the correct representation was consistent with achieving a correct solution.

Troubleshooting Strategies

Effective troubleshooting strategy use, including the ability to use multiple strategies when necessary, is another essential component of skilled troubleshooting (Johnson 1991; Johnson et al., 1992). The primary strategies used by each subject are presented in Table 5. The subjects selected troubleshooting strategies without any evidence of limited strategy performance during fault isolation. All subjects demonstrated an ability to use multiple strategic approaches including functional evaluation and half-split searches. As with the previous indicators of expertise, little difference exists between groups in their ability to use multiple strategies in a fashion consistent with expertise.

Insert Table 5 about here

Discussion

The findings of this study must be carefully interpreted, specifically with regard to the context of the study itself. The primary purpose of this study was to explore the relationship of context and electronics troubleshooting performance among experts, in context related tasks. The small sample size, while providing implications, precludes statistical analysis treatments and any inference or generalizability associated with them. Additionally, the population from which the subjects were selected, has a specific set of non-generalizable characteristics. The definition of the three context groups is dependent upon the activities they engage in, and mission of the industry or institution in which they perform troubleshooting. Given the limitations inherent in this study the results cannot be generalized to a larger population other than the limited sample of aircraft simulator electronics experts selected. The results can be used, however, to guide additional research efforts both in electronics troubleshooting expertise, and other domains of expertise.

Implications for Instruction

The general process skills associated with troubleshooting, and documented in this as well as other research efforts (Johnson, 1988; Johnson et al., 1992; Lesgold et al., 1986; Rasmussen & Jensen, 1974), must be included as an integral part of electronics instruction at all levels. All three groups of electronic experts engage routinely in troubleshooting activities that follow much the same process. The instruction of troubleshooting process at any level should include the elements of problem representation, hypothesis generation and evaluation, strategy selection, and verification of results. Additionally, the awareness of contextual references and the associated baseline assumptions they provide should be an explicit element of instruction, particularly when the goal of instruction is flexible expertise or general preparation for a non-specific role in the workplace.

An awareness of the effects of context, and the definitions of expertise resulting from context, can assist instructional designers and curriculum planners in providing relevant content from an appropriate reference. Electronics instruction aimed at maintenance technicians, but taught from a design point of view will appear to have little relevance to the program graduate or the employer. In addition to electronics instruction, curriculum planning for any multiple context endeavor should review the role of context, and particularly in instructional design guided by subject matter experts, ensure fidelity of instructional and target contexts.

Implications for the Study of Expertise

The role of context has important implications for the general study of expertise. A thorough examination of context could serve to more accurately define the limits of expertise and account for the irregularities often encountered in expert performance. Additionally, the systematic investigation of context can aid in the selection of an appropriate population of tasks for problem solving research.

In previous studies were novices and experts, or multiple groups of experts, have been compared little attention has been paid to context effects. Particularly in studies that compare groups, contextual references should be controlled for and acknowledged. Characterization of experts on a skill continuum with contextually disparate subjects may have little validity. Studies that have used a single subject matter expert, from a disparate context, may also lack foundational validity due to context effects.

The process of developing problem categories to guide expertise research efforts should account for variations in normally encountered task environments. Although the Contextual Problem Solving Continuum used in this study provides one level of definition it is likely that increasingly exact definitions can be developed with further research. Certainly, the tasks provided to experts by researchers, and the contexts they represent, are critical factors in studies of expertise. The selection of an inappropriate research context, or representative sample of tasks, may well provide an erroneous outcome.

Recommendations for Further Research

The most important result of this study may be the implications for further research discovered during this process. Certainly more research is needed that investigates the role of context in troubleshooting expertise, and the knowledge bases needed to support troubleshooting activities. Additional sources of study could include the manipulation of contextual reference data, differing problem presentations over multiple trials, and the development or use of other data collection avenues.

In-depth study of both design and production troubleshooting is needed. These studies could develop a body of knowledge for comparison to the existing maintenance process information. Multiple trials based on varying types of problems within each context is needed as well. An interesting variation would be providing references to the subjects when they exhaust their process, or as a function of multiple group experimental designs. Another promising approach may be the collection of verbal protocols in the natural environment over multiple occasions of work related troubleshooting. Constructing varying levels of context around problems could also provide useful insight. These presentations could range from written problems framed in a context "story problem" to introducing a problem set as representative of a context, or even realistic simulations of the various environments.

Care must be taken within studies that investigate context effects to limit the interference of research presentation. The smallest amount of problem introduction could influence the problem representations developed by the subjects. In order to gain additional insight into contexts, and frames of reference, it may be beneficial to stop the subjects before they attempt to gain any additional information through tests or system manipulations. A recursive interview at this point could provide some indication of initial context definition and subjects' frames of reference.

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CONTEXTUAL PROBLEM SOLVING CONTINUUM

Design/Development	Implementation/Production	Maintenance/Repair
Problem Characteristics: Novel presentations requiring the development of new knowledge and structure.	Application of a known process, or production of a viable design.	The continuation of a specified standard, through adherence to a conceptual structure, or pre-determined physical condition.

ELECTRONICS TROUBLESHOOTING CONTEXT APPLICATION

Design	Production	Repair
Goal Structure: Support the design process through consideration of theoretical constructs, from abstract concept to prototype.	Support the manufacture or construction of electronic devices from viable designs.	Discover a fault in an electronic system known to have previously been fully operational.

Figure 1 Contextual Problem Solving Continuum

Subject P1
Global Performance Profile

SEQUENCE	TIME	ACTIVITY	SUBSYSTEM	INFORMATION Number	ACQUISITION Type	EFFORTS Interpretation	RESULT	COMMENTS
1.	4	General Search	Power Input Gear Indicator	2	Visual	1.0	Fault Identified	Following schematic through subsystems.
2.	11	Fault Diagnosis	Gear Indicator	1 1 3 4	Visual Manipulation Continuity voltage	1.0	Component level solution	First hypothesis is something is backwards Checks to make sure the switches are wired according to schematic. Compares operation.
3.	4	General Search	Flap Motor Fuel Pump Bleed Air Valve Rotary Motor Beacon	5 3 2	Visual Auditory Voltage	1.0	Identifies Beacon	Verifies Flap Motor through voltage checks for proper switch engagement, sensory checks only for other subsystems.
4.	9	Fault Diagnosis	Beacon	2 1 1 1 6	Visual Auditory Manipulation Continuity Voltage	.9091	Device level solution	Initially searches for wiring fault. Verifies voltages up to and inside of housing including at cannon plug, but reports I'm stuck on this one, I'd replace the unit.
5.	2	General Search	Position Lights Instrument Lights Landing Lights Inverter	5	Visual	1.0	Identifies Fault	Notices wrong color on Position Light. Asks if Instrument Lights can be dimmed.
6.	12	Fault Diagnosis	Inverter	8 1 1 1	Visual Manipulation Continuity Voltage	.9167	No Solution	Investigates a logical wire fault that would trip a breaker at R3. Interprets voltage drop as a short. Says, I take it that is a known good Inverter

Figure 3 Episodic Performance Matrix

Subject P1
Landing Gear Indicator

EPISODE NUMBER	HYPOTHESIS STATEMENT	HYPOTHESIS LEVEL	HYPOTHESIS	HYPOTHESIS SUPPORT	SUPPORTING CHECKS	DECISION STATEMENT	HYPOTHESIS INTERPRETATION	COMMENTS
1	Something is backward	Subsystem	Improper voltage path to the instrument	Evaluation of schematic and symptoms	1-5 Visual, Voltage at input and output of switches	So we're looking at a switch that's not working right	Correct	Voltage checks at logical starting point
2	I'm checking the switch to make sure it's actually doing something	Component	Down microswitch is internally shorted	Previous hypothesis	6-7 Continuity of up and down microswitches	Both switches are working but one is backwards from the other	Correct	Compares function of both switches, and evaluates schematic for proper operation
3	So I believe that the switch is backwards	Component	Down microswitch is mis-wired	Previous hypothesis	8-9 Continuity check of down switch output terminals, swapping of output conductor	Works as advertised, OK	Correct	Checks output with continuity check prior to changing wires to "Make sure I'm not going to do anything that will cause smoke." Correct component level solution

Figure 2 Global Performance Profile

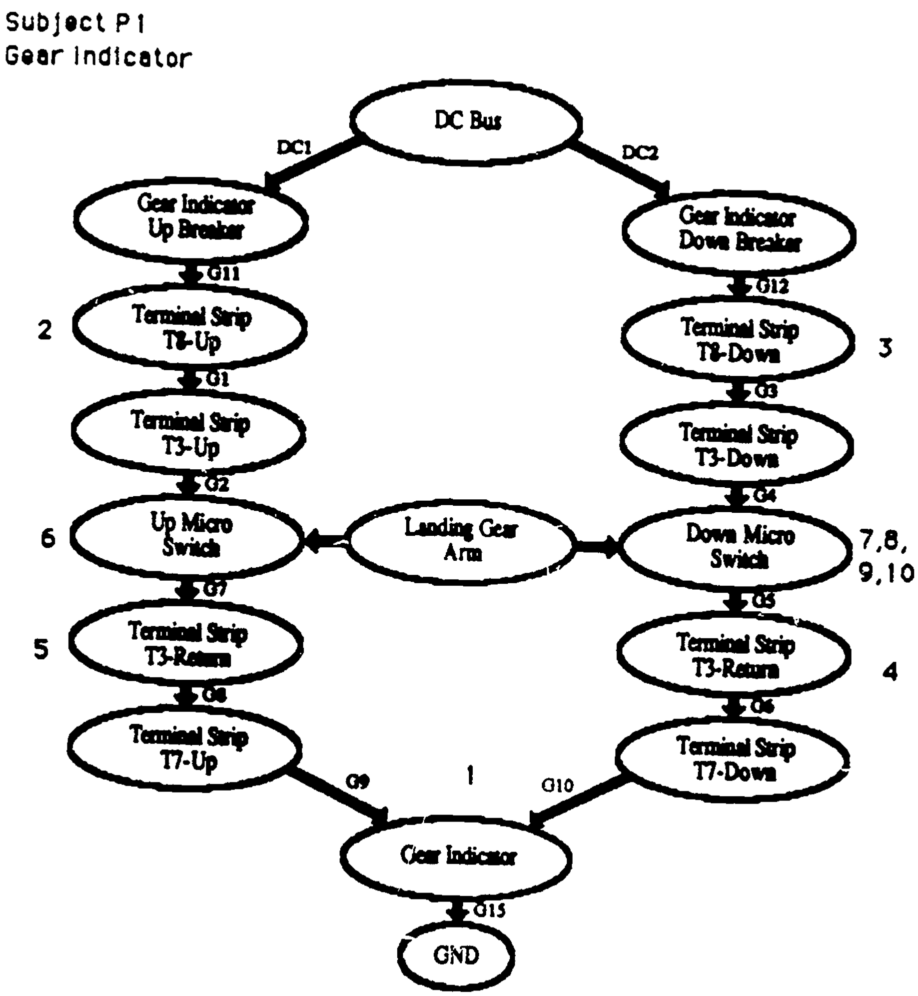
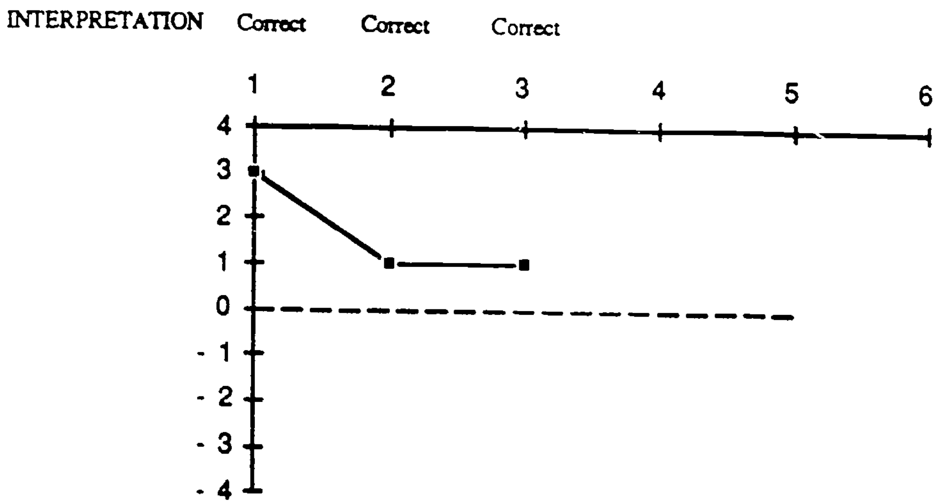


Figure 4 Functional Circuit Map

Subject P1 Gear Indicator Episodic Performance Graph
Correct Component Level Solution



Problem Space Relationship:
In Problem Space (1) System, (2) Subsystem, (3) Device, (4) Component
Out of Problem Space (-1) System, (-2) Subsystem, (-3) Device, (-4) Component

Figure 5 Episodic Performance Profile Graph

Table 1

Reported Context Expertise

Context	Subjects Reporting Expertise
Design	D1, D2
Production	P1, P2, D1, D2, R1, R2
Repair	R1, R2, D1, D2

Table 2

Correct Problem Solutions

Problem	Representative Context	Correct Subjects
Inverter	Design	D1, D2
Gear Indicator	Production	P1, D1, R1, R2
Rotating Beacon	Repair	R1, R2, D1

Table 3

Hypotheses Evaluation

Subject	All Problems Attempted			Correct Solutions Only		
	Correct	Incorrect	Incomplete	Correct	Incorrect	Incomplete
D1	.86	.07	.07	.86	.07	.07
D2	.50	.50	--	1.0	--	--
P1	.83	.17	--	1.0	--	--
P2	.33	.50	.17	--	--	--
R1	.57	.29	.14	.67	.22	.11
R2	.68	.05	.27	1.0	--	--

Table 4

Information Acquisitions

Subject	Correct Interpretation	Redundant Acquisitions	Recovery From Errors	Total Correct Interpretations	Problem Space Accuracy
			All Problems		
D1	.99	.10	.10	1.0	.73
D2	.75	.10	.25	1.0	.50
P1	.94	.06	.03	.97	.81
P2	.55	.35	.20	.75	.75
R1	.89	.14	.07	.96	.74
R2	.92	.19	.01	.93	.77
			Correct Solutions		
D1	.99	.01	.01	1.0	.73
D2	.57	0	.43	1.0	.86
P1	1.0	.10	--	1.0	.40
P2	--	--	--	--	--
R1	.90	0	.10	1.0	.93
R2	1.0	.05	--	1.0	.76

Table 5

Troubleshooting Strategies

Subject	Beacon	Gear Indicator	Inverter
D1	Functional evaluation Visual inspection Half-Split voltage	Functional evaluation Visual inspection	Functional evaluation Visual inspection Half-Split voltage
D2	Functional evaluation Reverse voltage	Half-Split voltage	Functional evaluation Half-Split voltage
P1	Functional evaluation Visual inspection Physical half-split Reverse voltage	Functional evaluation Operational comparison	Functional evaluation Visual inspection Physical half-split
P2	Trial and error Forward voltage	None	Functional evaluation Physical half-split Half-Split voltage
R1	Functional evaluation Experimentation Physical half-split Visual inspection Reverse voltage	Functional evaluation Experimentation	Functional evaluation Experimentation Physical half-split Visual inspection Half-Split voltage Exhaustive search
R2	Functional evaluation Experimentation Reverse voltage	Functional evaluation Experimentation Reverse voltage	Functional evaluation Physical half-split Visual inspection Forward continuity Exhaustive search