Expert error.

The case of trouble-shooting in electronics

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Abstract. An expert trouble-shooter is a subject who has a great deal of experience in his activity that allows him or her to be very efficient. However, the large amount of problems he or she has experienced tends to rigidify his or her strategies due to empirical learning and application of [symptom-fault] co-occurrence rules. We defend the hypothesis that experts' errors depend on the knowledge of these co-occurrences. Our experiment supported this point of view: expert trouble-shooters in electronics implement non-relevant actions in an atypical symptoms configuration.
From an operational point of view, human is an active component of systems and the final dependability partly relies on human reliability. More specifically, human operators are strongly involved in maintenance and trouble-shooting activities. One then has to know about the cognitive processes involved in expert error and integrate this knowledge in the design of systems.

Introduction

A lot of research has put in evidence the performance (rapidity of the actions) and the reliability (precision) of experienced operators in many domains of activity. The approach of this paper slightly deviates from this conception as it aims at exhibiting the limits of expertise in the core of its foundations. The experiment will show that an expert trouble-shooter in electronics may be sensitive to a bias. He may perform errors and activate non-relevant knowledge.

Research in problem-solving showed that experts are specialized in an automated processing mode. This preferred rule-based automatisation may imply that experts' errors mainly depend on this mode of reasoning. An atypical configuration of symptoms should then impair the reliability of expert trouble-shooters.

This article will mainly focus on expert trouble-shooters' activity in natural conditions of work in order to identify some psychological elements relevant to work situations. The paper begins by presenting some theoretical data about expertise in diagnosis. This will serve as a frame for the experiment. The discussion will then attempt to link the results with the existing theoretical data and to provide an operator-centered point of view about systems dependability.

Expertise in diagnosis

The theoretical position of this paper defends the idea that experienced operators (hereafter called experts) solve problems by extracting surface patterns of information from the environment in order to identify a possible solution [1]. The detection of such patterns permit the triggering of what Rasmussen [2] calls short-cuts, that is to say a matching process between a configuration of data and an action.

The need to make fast decisions favours diagnostic methods based on pattern recognition rather than on underlying processes [3]. Diagnosis operations of experts rely on probabilities [4, 5]. They activate tests of some elements of the system that, in the past, have most often explained the symptoms. These tests may be executed sequentially, from the most probable to the least probable [6].

Diagnosis can be considered as a form of reasoning whose goal is to identify causes of facts assessed as abnormal [7, 8]. Diagnosis is involved in a wide variety of situations where it regulates the activity. Such situations include among others the monitoring of a nuclear reactor [9], monitoring a furnace [10], piloting an aircraft [11], fire-fighting [12], decision making in an anti-aircraft defence system of a surface ship [13], decision making on an offshore platform [14]. Diagnosis is also present in static situations. This is the case of trouble-shooting. Studies that have dealt with natural trouble-shooting include an automobile ignition system [15], a running engine [16], an electronic circuit [17]. In these situations, fault-finding represents the main part of the activity and the diagnosis process mainly develops as a consequence of the operator's actions. In this research, diagnosis will be considered as a static trouble-shooting task.

Symptoms detection is a major phase in the trouble-shooting process. It is a selection of data. It is performed as a function of the weight that the operator assigns to the different available sources. This strategy relies on the knowledge of past occurrences of malfunctions and on their causes. It allows expert operators to implement a symptomatic trouble-shooting [7, 2, 4, 5]. This research strategy quickly reduces the number of components possibly at fault with very few tests. It is a pattern recognition process where symptoms are compared to possible causes in order to find a relation that will indicate a specific fault [8, 18]. The symptomatic strategy is generally opposed to the topographic strategy where fault-finding consists in searching for a fault by following a physical support such as a cable or a flux. It is processed at a knowledge-based level of control -typical of the novice operator- that implies heavy and numerous operations.

Theoretical position

In the classical conception, expertise relies on a capacity to activate knowledge relevant to the task and to efficiently categorize problems [19]. This paper puts this conception of expert reasoning in question. The large amount of problems trouble-shooters meet through their experience tend to rigidify the strategies they implement.

This is mainly due to empirical learning of [symptom-fault] co-occurrences. Expert trouble-shooters may then be sensitive to biases. They may produce errors and activate non-relevant knowledge, especially in an atypical configuration where the symptoms do not match the usual causes.

The experiment will attempt to show that experts' errors rely on a rule-based association that occurs when the situational data are not optimal for such an association. As novices' reasoning processes mainly rely on a knowledge-based level of control, they should not be sensitive to this bias. They are expected to show more efficient diagnostic reasoning processes in some phases of the trouble-shooting activity.

The general approach developed in this paper is a naturalistic one. It consists in studying a trouble-shooting task in the conditions of the real work. The psychological interest is to understand the mechanisms underlying expert error. This study also has an operational interest since an operator performing an error when trouble-shooting may impair the availability and the dependability of a system.

This research will study a trouble-shooting task on an electronic circuit where a fault was implemented. This fault exhibits frequent and well-known symptoms whereas the actual cause is rare. This discrepancy should be an interesting feature in order to study expert error in diagnosis.

Method

Subjects

All participants were male and volunteers. There were 10 expert and 9 novice electronics operators. Experts had between 8 and 40 years of experience (m=18,9; s=9,1). There were 8 military operators (Air Base 278 at Ambérieu and Naval Base at Toulon, France) and 2 civilians. All of them were professional operators. Novices were baccalaureat students in a technical school (Lycée Vauvenargues, Aix-en-Provence, France) who had been studying electronics for 2 years.

Materials

Diagnosis devices (multimeter, oscilloscope) and two technical diagrams (an implantation diagram and a theoretical diagram, in A4 format) were provided to the subjects. The implantation diagram (Fig. 1) is a representation of the topographic aspect of the circuit. The theoretical diagram (Fig. 2) represents the connections between the components.
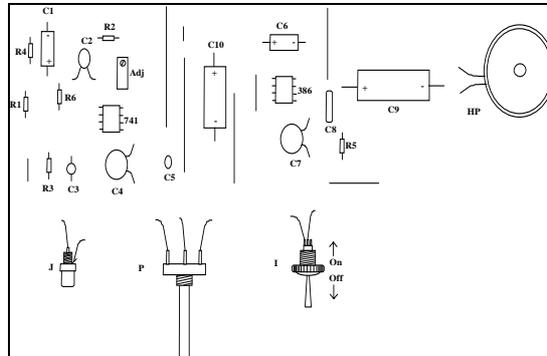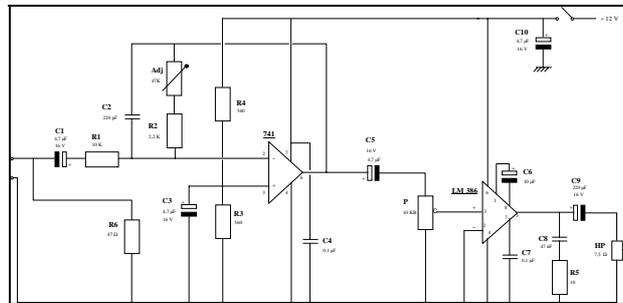
Fig. 1. Implantation diagram

Fig. 2. Theoretical diagram

Experimental device

The device[1] subjects had to trouble-shoot was a simple low-frequency amplifier that comprised two amplification stages, each comprising an integrated circuit (IC). The first stage comprised the IC741 ; the second one comprised the IC386. The assembling of the circuit conformed to conventions. The board (24cm x 8cm) where the circuit was assembled allowed the subjects to visualize the tracks and the connections between the components. The inputs of the circuit were a FM radio signal plugged into the input jack (component J) and a DC 12V power supply. When the fault was located (see below) and the faulty component replaced, some FM music was broadcast through the loud speaker.

Description of the fault

The fault was on the C7 condenser. Although this fault is very rare, it is similar to another fault -an integrated circuit (IC) failure- that can usually be diagnosed rapidly. C7 was short-circuited with a thin invisible weld wire. In this faulty condition, the condenser C7 switched the output signal of the IC386 to the mass track (Fig. 3). When subjects tested this IC, they tested the input, measured a signal, then tested the output and measured no signal. The symptoms led the subjects to suspect the connected IC386 as the cause of the fault.
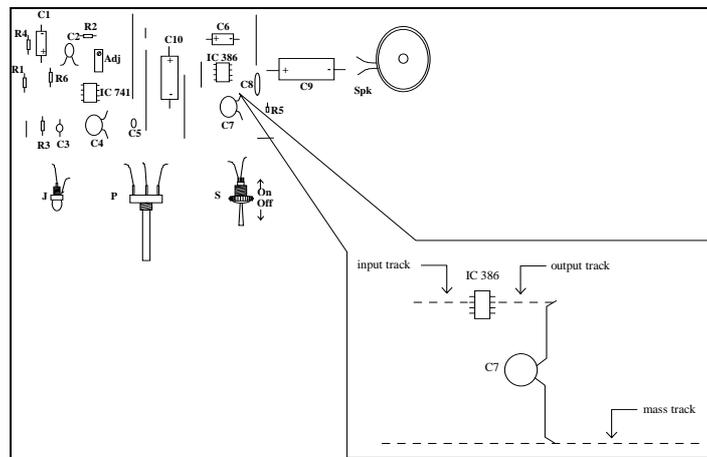

Fig. 3. Description of the fault.

Procedure

The subjects worked in their usual workshop. After the instructions were read, the device was turned on (in configuration of fault) and the diagnosis began. The experimentation was videotaped in order to keep track of the operator's actions. The trouble-shooting process stopped when the subjects found the faulty component or when he gave up. No advice was given to the subject and there was no time limit. The experiment could stop with the cause of the fault not being discovered.

Variables

There is one between-subjects variable: expertise (expert *vs.* novice). Percentages in the total number of operations were computed for the variables 5 to 14. They allow the extraction and comparison of proportional data.

1 / *Fault located or not.*

2 / *Time*. This referred to the number of minutes that separate the beginning of the experiment to the localization of the fault or the moment when the subject gave up.

3 / *Total number of operations*. An operation is considered as a test (measure, disassembly, etc.) or the consultation of a source of information that is external to the circuit itself (e.g. diagrams).

4 / *Number of different elements covered by the operations*. This variable measures the diversity of elements tested by the subject.

5 / *Percentage of operations on the IC386.*

6 / *Percentage of operations on the IC741.*

7 / *Percentage of operations on the ICs (741 + 386).* ICs are active and fragile components. A high number of operations on these components highlights the implementation of a frequency heuristic.

8 / *Percentage of operations before the 1st operation on the IC386.*

9 / *Percentage of operations before the 1st operation on the IC741.*

10 / *Percentage of operations before the 1st operation on an IC*. This variable is an indication of the progression of the diagnosis before the 1st operation on an IC.

11 / *Percentage of operations on resistances and condensers*. Resistances and condensers are passive and reliable components. A high number of operations on these components indicates some remoteness from the frequency heuristic.

12 / *Percentage of operations on C7*. C7 is the component at fault. It is short-circuited but it is usually reliable. It is not a good candidate for the fault.

13 / *Percentage of operations before the 1st operation on C7.*

14 / *Percentage of operations after the 1st operation on C7.*

Predictions

Experts have the greatest amount of experience in this experiment (Variable 1). The total number of operations (V3) should be higher for experts than novices as the fault is an atypical one. However, this variable has to be considered in the context of the final result of the trouble-shooting process. On the other hand, the number of different elements covered should be lower for experts than novices since experts are expected to test a smaller diversity of components (V4).

The percentage of operations on the IC386, on the IC741 and on the ICs (V5, V6 & V7) should be higher for experts than for novices. In the same way, considering the expected saliency of the ICs, the percentage of operations before the 1st operation on the IC386, on the IC741 and on an IC (V8, V9 & V10) should be lower among experts. The hypothesized implementation of the frequency heuristic supports this set of predictions.

Through their extended practice, experts built an empirical knowledge about the relative reliability of the resistances and condensers. The percentage of operations on these components (V11) should be lower for these subjects.

Finally, as C7 is a very reliable component, the percentage of operations on C7 (V12) should be lower for experts than for novices. For the same reason, the

percentage of operations before the 1st operation on C7 (V13) will be higher for experts.

The variables 2 (time) and 14 (% of operations after the 1st operation on C7), although not introducing any hypotheses, should provide some additional data.

Results

The data were analysed through an analysis of variance. Broadly speaking, results did not reject the hypotheses.

Experts located the fault more often than novices (5/10 experts versus 2/9 novices). Expertise, regarding the final state of diagnosis, remained a factor of competence. But some areas of the expert trouble-shooting process were sub-optimal.

The experiment stopped when the cause of the fault was located or when the subject gave up. Experts spent more time than novices before reaching this point (experts=47 min; novices=30,22 min) ($F_{(1,17)}$=4,129; p=.058). Contrary to our prediction, experts and novices did not differ significantly on the total number of operations and on the elements covered by the operations.

As Fig. 4 shows, the percentage of operations on the IC386 is larger among experts (experts=25,9; novices=3,6) ($F_{(1,17)}$=10,888; p=.004). These subjects also showed a larger percentage of operations on the IC741 (experts=13,2; novices=2,12) ($F_{(1,17)}$=13,095; p=.002). On the whole, the percentage of operations on the ICs (741 + 386) was larger for experts than for novices (experts=39,2; novices=5,6) ($F_{(1,17)}$=30,59; p=.0000). As predicted, expert operators over-valued the importance of ICs in the circuit.

Experts and novices differed significantly on the percentage of operations before the first operation on the IC386 (experts=4,66; novices=48,23) ($F_{(1,15)}$=16,035; p=.001), on the percentage of operations before the first operation on the IC741 (experts=5,77; novices=26,39) ($F_{(1,12)}$=6,414; p=.026) and on the percentage of operations before the first operation on ICs (experts=4,47; novices=43,7) ($F_{(1,15)}$=11,881; p=.003). Generally speaking, experts performed fewer operations than novices before testing an IC. These findings were considered as evidence for the implementation of the frequency heuristic.
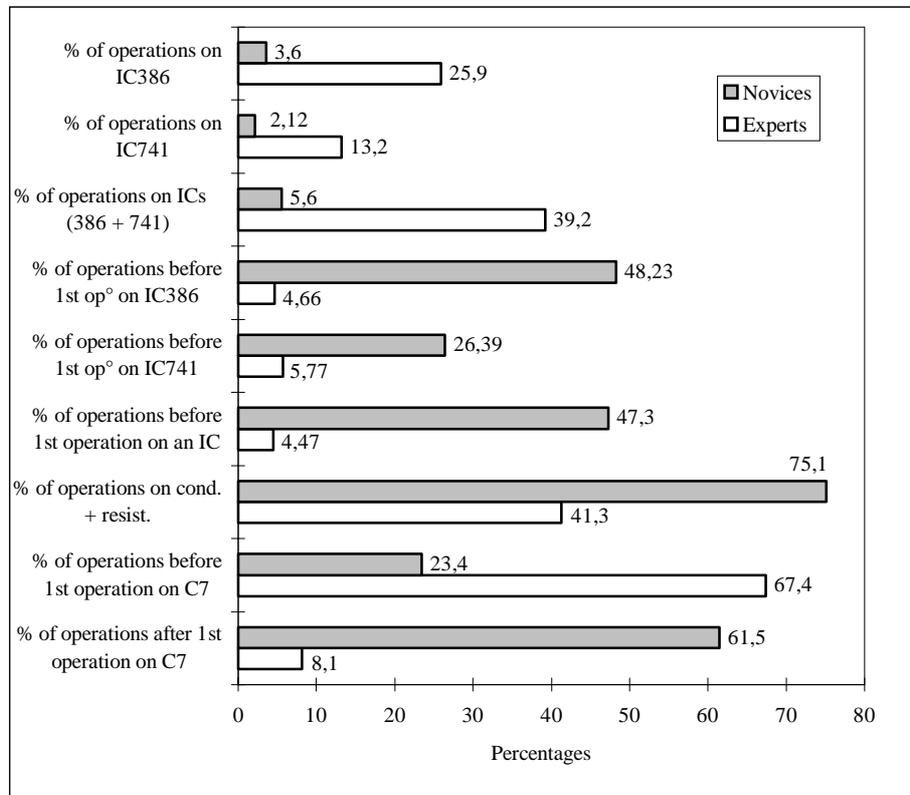
Fig. 4. Overview of significant results.

The percentage of operations on resistances and condensers showed a significant difference (experts=41,3; novices=75,1) ($F_{(1,17)}$=11,34; p=.003). As predicted, the operations performed by experts on resistances and condensers represented, in comparison to novices, a small part of the activity.

The percentage of operations on C7 did not exhibit any difference between experts and novices but the percentage of operations before the first operation on C7 tended to be reliably different (experts=67,4; novices=23,4) ($F_{(1,10)}$=4,086; p=.07). Novices tested the faulty component sooner than experts. This result supported our hypothesis of a possible implementation of sub-optimal operations by experts. Nevertheless, the percentage of operations after the first operation on C7 showed that experts virtually finished trouble-shooting after having tested C7 for the first time (experts=8,15; novices=61,56) ($F_{(1, 11)}$=30,44; p=.0002).

Discussion

There were not any significant differences between the two groups of subjects on the number of operations and on the number of elements covered. On this latter point, one cannot conclude that the expert focused on a more narrow set of components than novices did. Subjects did not differentiate themselves on the percentage of operations on C7. Experts, when testing this component, noted that it was at fault. This measure marked the end of their trouble-shooting. On the other hand, novices hardly ever located the fault. As a consequence, they performed very few operations on C7. These two different behaviours explain the absence of any difference on this variable.

Among the experts who did not locate the fault (n=5), two performed operations on C7. How may an expert test C7 without locating the fault? One of these two subjects asserted, when measuring C7, that he had encountered "some difficulties in testing it". A possible explanation lies in the confidence of the operator in the measure. An alternative explanation refers to the consistency of a measure regarding the representation of the fault. If a component, even at fault, does not allow the operator to better understand the symptoms, then this component is not assessed as responsible for the symptoms.

Experts performed more operations on the IC386 and the IC741 than novices. They also tested ICs earlier and they perform less tests on resistances and condensers than novices. These data support the idea that experts use their knowledge of the relative reliabilities of components.

Novices tested the C7 component sooner than the experts although the latter virtually finished their diagnosis once C7 was tested. This result can be discussed in the light of the concept of cognitive economy. As resistances are reliable components, experts gave priority to ICs as candidates for the fault. Consequently, a small number of operations before the first test on this kind of component would be inconsistent with the principle of economy, even if it would lead the subject to locate the fault faster in our circuit.

The frequency heuristic associates symptoms to their causes depending on the past occurrences. It is a powerful tool in the case where symptoms reflect the structural state of the circuit. But this trouble-shooting method can generate errors when symptoms are not those usually associated to the fault. Then, the frequency of the past occurrences is no longer the best support of the diagnosis process as it causes experts to focus on non-relevant components.

Sub-optimality

Three points of sub-optimality were listed:
1. Experts performed more operations than novices before testing the faulty C7 for the first time.
2. Experts focused on ICs. Considering the current fault, this behaviour is sub-optimal since the ICs are not responsible for the fault. The concept of *frequency bias* may account for these two latter sub-optimal behaviours.

3. Experts spent more time than novices searching for the cause of the fault. Time is only a superficial indicator for cognitive activity since experts found the fault more often. However, one must keep in mind that speed is not an invariant among experts.

These points of sub-optimality support the idea a) that novices can exhibit more efficient behaviours that experts do and b) that expert errors mainly rely on a matching process used as a problem solving strategy. Expert operators tend to look for an optimal solution with a minimal cognitive expense even if there is not any guarantee about the results. This risk is constrained since, in most cases, the operator cannot reason in a systematic and exhaustive way on the whole data and hypotheses.

Limits of the study

First, the conditions of the experiment are exceptional in comparison to the professional activity. Even if an error from an experienced operator is always possible whatever his field of activity, expertise is more a security factor than an error generator. Secondly, expertise, as in the present research, is often introduced as a binary concept. However, it is not a simple expert/novice distinction, even though such a dichotomy is experimentally useful. This conception does not fit the continuum of a life-scale process of knowledge acquisition.

What link with systems dependability?

The interest in studying the dependability of systems goes far beyond the classical hazardous industrial processes (nuclear plants, transports, space, etc.). Nowadays, the existence and survival of some information systems totally relies on the availability of the components that underlie their security. In such systems (e.g. the stock exchange), when a physical problem occurs, the rapidity and precision of the intervention represent heavy operational stakes. For this reason, when a human operator attempts to recover the initial state of the system, he or she has to reach an optimal level of performance. If the intervention comprises sub-optimal phases (such as those reported in this paper), then some aspects of the dependability of the system may be impaired:
- the system may no longer be available to its users;
- continuity of the network in which the system may be inserted can be broken;
- confidentiality of the information in the system may be affected if a protection function is impaired.

The weight of humans' actions in information systems should cause the research in dependability to integrate a cognitive approach. Humans are parts of a system. This is a first reason why one should improve their level of performance, particularly if they are active components of dependability (e.g. maintenance operators). Moreover, cognitive ergonomics have qualitative and quantitative methods that can serve any domain of human activity. The dependability of computerized systems takes on some importance since:

- computers have an increasing role in all industrial and domestic tasks;
- human operators play a dynamic role in the interaction with machines.

There are at least two research orientations that may improve the reliability of human-machine interaction:

- keep on formalizing human activity in order to accurately identify the causes of (expert) operators' errors;
- integrating the possibility of human error occurrences in the system's architecture in order to implement tolerance margins.

Conclusion

This experiment was conducted in order to know on what expert error in trouble-shooting depends. From the experiment's results, it has been shown that expert operators in electronics trouble-shooting a circuit over-value the importance of the components that, most of the time, explain the symptoms. This behaviour, called *frequency bias*, explains why expert operators use intuitive statistical rules to implement actions. After previous similar results in electronics (Besnard & Bastien-Toniazzo, 1999) it seems that there is one more piece of evidence that experts use surface features when trouble-shooting. They tend to activate procedures from symptoms detection and this matching process forces them to accept a risk of error.

Accordingly, if one aims at building dependent systems where humans may have a role, then one has to take into account the cues and the cognitive processes upon which the expert error depends.

Acknowledgements

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