TROUBLE-SHOOTING IN MECHANICS : A HEURISTIC MATCHING PROCESS

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Abstract: This paper deals with expert operators' reasoning processes in trouble-shooting. We want to know more about the information that experienced operators use. In a previous study (Besnard & Bastien-Toniazzo, 1999; Besnard, 2000), we studied electronics trouble-shooting. We found that experts used surface cues in order to implement heuristic rules even if the latter are not relevant to the current fault. We now wish to study the field of mechanics. An experiment was conducted in order to test the hypothesis of a heuristic rule-based level of control responsible for errors among experts. This paper adopts a naturalistic and ergonomic point of view about trouble-shooting in mechanics. Our results show that expert mechanics operators' errors rely on heuristics in the trouble-shooting process. This strategy relies on an automated matching process between symptoms and procedures. Although this strategy is usually powerful, it is rigid and may lead the operator to not locate the fault if the latter is atypical.

Key words: Expertise, trouble-shooting, mechanics, rule-based reasoning.

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1. Introduction

A lot of research has highlighted the fact that expert operators implement more efficient problem solving strategies. To the authors, the efficiency of these strategies relies on a matching process that trouble-shooters use in order to find a correspondence between the current case and a set of possible faults. This is the topic that we have investigated in this paper, in the case of the trouble-shooting process of an atypical fault.

The theoretical part (sections 2 to 6) introduces the concepts of expertise and trouble-shooting. In the second part (section 7), the experimentation is presented. The presentation of the results (section 8) and the discussion (sections 9 to 11) take place in the third part of the paper.

2. Expertise

In familiar situations, experts implement more efficient problem solving modes than novices. They save resources in working memory (Baddeley, 1992), process information with a reduced load and resist its increase (Bisseret, 1970). The differences between experts and novices may be explained in terms of efficient knowledge organisation (Posner, 1988; Robbins *et al.*, 1996; Custers, Boshuizen & Schmidt, 1996). According to other authors, experts identify a pattern of data when processing information. Several studies showed that when a pattern of data must be encoded, structural changes constrain the storage. This result was found in chess playing (Chase & Simon, 1973), in software programming (Soloway, Adelson & Ehrlich, 1988; Barfield, 1986), in the recall of medical data (Norman, Brooks & Allen, 1989) and in bridge playing (Frensch & Sternberg, manuscript). According to Hardiman, Dufresne and Mestre (1989), Zajchowski and Martin (1993) and Smith (1992), the experts' reasoning process would rely on the identification of a structure of a problem, contrary to the novices' reasoning process that would rely on surface cues. The authors' position on this specific question is that both novices and experts make their reasoning process rely on surface cues. The point is that experts can match what they perceive from the problem with a procedure that has already been applied and tuned. Instead, novices have to build a representation and perform a deductive reasoning process. As a paradoxical consequence, novices show a great amount of cognitive resources involved in a reasoning process which happens to be prone to errors. This could account for the well-known difference in the level of performance achieved by novices and experts.

Rasmussen (1986; 1993) and Fink and Lusth (1987) mention short-cuts between situational cues and procedures to be applied. These short-cuts would support the efficiency of experts' reasoning. The positions of Reason (1990), Zapf and Reason (1994), Salminen and Tallberg (1996) and Hoc (1996), concerning the reasoning process, rely on this conception. Expert activity is controlled by stored pre-programmed configurations of instructions processed at a rule-based level. The knowledge-based level of control is implemented in unknown situations for which actions have to be planned in real time and controlled. As expertise grows, the rule-based level of control tends to prevail. Generally speaking, rules are domain-specific and are triggered from environmental activators. They permit the fast processing of typical situations for which the expert acts on the basis of an over-learned identification (Konradt, 1995). The conception of expertise as a rule-based reasoning process is the closest to our point of view.

3. Cognitive resources savings

One of the core features of expertise is an optimal performance with a minimal mental cost. This strategy forces the experts to implicitly accept a risk as numerous hypotheses may not tested for a given case. However, taking this risk is constrained by the fact that the human cognitive system cannot cope with the complexity of the total amount of data present in a given environment (Amalberti, 1991; Rouse, 1978). One of the solutions developed by experts is making the reasoning process rely on the rules quoted above. Some of these rules are heuristic as they are not meant to provide the right answer to any problem but instead, under some acceptable uncertainty, to be efficient in routine situations. The heuristic rules are refined as a function of the frequency of triggering for a given set of data. For instance in trouble-shooting, the more frequent a given [symptom *x* - cause *y*] association, the more likely it is that the rule encoding this association will prevail on the next occurrence of symptom *x*. The sensitivity of rules to frequency increases with experience since the knowledge base is more representative of the possible instances of a fault (Weber *et al.*, 1993).

In supervision situations, where an operator has to manipulate a set of parameters in order to keep a system state within its normal boundaries, the interest of intuitive statistics (which support the rules refinement process) is the possibility of allocating free cognitive resources to a second parallel task, e.g. supplementary data collection and anticipation of future system states. Basically, the cognitive resources savings obey the principle of the smallest cognitive effort. The operator seems to employ as little cognitive resources as possible for a given goal. In fact, the expert attempts to evaluate the trade-off between the goal that can be achieved and the mental cost implied by this goal. This is the case in trouble-shooting situations, especially when the situation includes time constrains.

4. Experts' diagnosis

Diverging from the classical conception that diagnosing is finding the cause of an effect in a system having no relation with time (see Dale, 1957 and Rouse, 1978), diagnosis may be processed on dynamic systems (Hoc & Amalberti, 1994, 1995). These can be defined as systems whose states may change autonomously over time without any intervention of an operator. In those systems, diagnosis mostly consists of predicting future states and their consequences (Cellier, Eyrolle & Mariné, 1997). For Brehmer (1987, 1996), dynamic tasks imply a series of inter-dependent decisions. The state of the task changes both autonomously and depending upon the actions of the operator. He or she must then act in real-time in order to revise his or her task representation and set priorities in the actions (Sundström, 1993; Randel & Pugh, 1996). One not only has to know what to do and when to do it but also how (Kersholt, 1995; Brehmer & Svenmark, 1995), with what risk (Pascoe & Pidgeon, 1995) and if a potentially faulty deviation exists (Svenson, 1990; Samurçay & Hoc, 1996).

There is a wide range of situations where a diagnosis may be involved, from highly dynamic ones (e.g. piloting, see Amalberti, 1992), where anticipating and stabilising is a major issue, to static ones where the core activity is finding a cause explaining the symptoms. As this study deals with a static trouble-shooting task, we are now considering diagnosis as a means to control a static situation.

A system can be described as static if the operator needs to act on it in order to change its state. Under static conditions, diagnosis is a form of reasoning whose goal is to identify the causes of abnormal facts and understand the causes of the observed symptoms (Cellier, Eyrolle & Mariné, 1997). It begins with the observation that the system deviates from what is expected. Formally speaking, the operator tests hypotheses about the cause of the trouble in terms of change in the system's structure (Milne, 1987; Mozetic, 1991). In practice, expert diagnosis rather consists in matching the perceived symptoms with a set of stored data. This applies in medical (Medin, Altom, Edelson & Freko, 1982; Boshuizen, Hobus, Custers & Schmidt, 1991; Custers *et al.*, 1996) or clinical diagnosis (Mumma, 1993) where symptoms are linked with a class of disease or are recognised as a well-known pattern (Norman *et al.,* 1989). Experts in diagnosis (physicians, trouble-shooters) use pre-compiled rules and response plans (Gaba, 1991) based on the identification of these patterns of symptoms. For instance, if the present case is judged to be similar to a past one, the result of the past judgment will serve as a possible explanation for the present case (Liu, 1991). This mode of reasoning is implemented by subjects who have a great deal of experience in a particular task (Reed & Johnson, 1993). In that context, some forms of error may appear when the operator's reasoning process relies on matching rules for coping with the complexity of the situational data.

5. Diagnostic rules

Among the different knowledge structures that one could find in an expert's mind, the authors wish to introduce schemes. They are a means for saving cognitive resources thanks to an automatisation of the behaviour (Amalberti, 1996). Schemes are high-level mental structures that underlies every aspect of human skills (Reason, 1990). They can be seen as a complex blocks of organised knowledge that can be adapted to contextual variations (Richard, 1990). They comprise bits of knowledge and the way this knowledge must be used (Guillevic, 1991). Schemes need specific activators to trigger. They comprise a procedure (a plan) and the knowledge of the final problem state that must be achieved.

A scheme allows to rapidly process frequent situations by allowing one to match a solution with the data that have been extracted from a problem statement. This matching is underlied by the operator having extended experience with a great number of problems belonging to the same class. Bollon and Channouf (1993) found an analogy between schemes and Rasmussen's (1986) short-cuts. Just as schemes do, short-cuts set a functional link between a pattern of situational data and an action. But Ramussen's model (1986) not only accounts for what schemes account for (activators, automatisation of problem solving, cue-action matching). It also integrates them in a single architecture where both experts' and novices' reasoning mechanisms are described. Finally, as Ramussen's short-cuts are a support for a heuristic rule-based reasoning, we decided to make our theoretical framework rely on this model.

The rules that are used by experts when reasoning are selected on the basis of their frequency of use. Each rule is associated with a strength that reflects its past usage (Anderson, 1993). During the learning process, the rule becomes more and more specialized and it will become activated in a smaller and smaller set of cases. It will finally be activated only in the situations where it is the right thing to do (Ohlsson, 1996). In order to save cognitive resources, experts encode together a given behaviour of the system and some failed components as a heuristic rule (Pazzani, 1987). Expert fault-finding then becomes the application of the rule that best explains the symptoms or that is most often activated in the current configuration of symptoms (Nooteboom & Leemeijer, 1993). The rules are implemented sequentially from the least to the most probable (Bereiter & Miller, 1989). But man is a fallible statistician (Patrick, 1993) and thus activation of procedures on the basis of the frequency of the symptoms may generate irrelevant actions. Experts act on the basis of an optimised balance between cognitive load and probability of error. Their decisions reflect the existence of an operational trade-off where a residual risk is accepted if a given rule provides an acceptable solution in the most common configurations of problems (Amalberti, 1996).

In a faulty configuration, an expert attempts to identify a pattern of symptoms in order to match it to a rule. The pattern can be recognized even if the current symptoms are not linked with their usual cause, in an exceptional occurrence for instance. The diagnosis is then carried out on the basis of a partly irrelevant set of data and the operator takes into account a restricted set of actions (Besnard, 1999; Hoc, 1996). This is the case of an operator who launches a test procedure from the identification of typical cues without searching for further data. This could be reported as a form of rigidity. In such circumstances, it is a distinct possibility that expert's problem solving strategies do not tend to be more and more flexible. In some cases, one could even argue in favour of the contrary. This is the idea we attempted to defend in this research.

6. Theoretical position

We have seen that expertise could be underlied by an efficient organisation of knowledge. A cue-action matching process has also been proposed to account for the performance of experts, leading to conceptions in terms of rule-based reasoning processes. In our view, these rules are the basic cognitive mechanisms that expert operators use in trouble-shooting. In turn, the short-cuts supported by these diagnostic rules rely heavily on the detection of patterns of data. Such a diagnostic process is usually very efficient and reduces the cognitive load in comparison to a knowledge-based reasoning process. However, the expert operator implicitly accepts the risks induced by triggering a non relevant rule when an arrangement in the environmental data has erroneously been interpreted as a known pattern.

Contrary to experts, novices cannot detect the saliency of a given symptom as their knowledge does not include a hierarchical classification of possible symptom-fault pairs. They use symptoms in order to build a representation of the fault and this representation is updated incrementally as tests are performed. Although one cannot totally exclude an inferential reasoning mode among experts, our position is that that they mainly use heuristic rules. Our theoretical hypothesis defends the idea that if some salient situational features of a situation prompt the expert to launch a frequent rule, then he or she may neglect further cues and apply this rule. This rule may trigger an irrelevant chain of actions if it is activated from an incomplete set of activators (Reason, 1990). Experts may perform this kind of error because of the strength of the functional link between a frequent pattern of symptoms and the rule associated with this pattern. However, the highly probable cognitive resources savings associated with the implementation of this rule-based trouble-shooting process justifies taking the risk of an irrelevant rule being triggered.

7. Method

We have chosen to experimentally study mechanics. There are three reasons for this. First, it is a natural domain of competence. This point is important since our goal is getting data about cognition in ecological conditions of work. Secondly, as far as we know, very few studies have been conducted about trouble-shooting in mechanics involving a running engine. Thirdly, this choice is an attempt to extend previous results on expert trouble-shooting (Besnard & Bastien-Toniazzo, 1999; Besnard, 2000) to a new field of activity.

7.1. Subjects

The subjects were 8 novice and 8 expert mechanics. All subjects were volunteers. Experts were professional mechanics ranging from 10 to 33 years of experience (m=17.37, s=7.63). Novices were apprentices in a technical school that had been learning mechanics for two years. All subjects were male.

7.2. Material

The experiment took place in the workshop where the subjects usually worked. It was a well-known environment to them. All the tools that were involved in the experiment were identical across subjects and were quite familiar to them.

7.3. Tools

The subjects could only use hand tools (screwdriver, wrench, etc.) from a single toolbox that all subjects used. Under some specific conditions (e.g. a special wrench), the subjects could use tools that did not feature in the toolbox. Electronic tools and multimeters were excluded from the experiment in order to standardize the experimental conditions across subjects[1]. The subjects could consult the technical book of the engine.

7.4. Device

The experimental device was a running petrol Renault 25 engine mounted on a trailer. Every element of the engine was accessible. Some peripheral components of the engine were moved from their original location so that the device could be transported. These components were the battery, the air filter (directly connected into the air collector on the carburettor), the petrol tank (moved to the aft of the trailer), the coolant tank and the high tension (HT) module. These displacements did not alter the functioning of the engine.

7.5. Description of the fault

With a petrol carburettor engine (which is the kind of engine used for the study), the piston descending in the cylinder creates a depression (first stroke). In the beginning of the descent, the inlet valve opens and the mixture of air and petrol is sucked in from the carburettor via the intake manifold. Then the inlet valve closes and the piston rises to compress the mixture (second stroke). At the top of the movement of the piston, the plug sparks and makes the mixture explode. This explosion strongly pushes down the piston: this is the motor stroke (third stroke). Then the exhaust valve opens and the piston rises again to push the burned gases out (fourth stroke). The exhaust valve closes, the inlet valve opens and the cycle starts again.

In the experiment, the fault was caused by an aluminium plate obstructing the intake tube of cylinder #4. The plate caused the following symptoms:

a) The engine worked with heavy vibrations since the gases the cylinder #4 did not explode;

b) The plug of cylinder #4 sparked but it was greasy due to some oil entering the cylinder.

These symptoms can be caused by several natural causes: a hole in a piston, a leaking valve, or a problem with a ring[2]. The closeness of the plate-caused symptoms to natural ones supported our choice of obstructing an intake tube[3].

The experimental situation where the subjects were placed was an artificial one and there were very few chances for them to correctly diagnose the problem. Nevertheless, there are two main interests in studying such a fault. First, we must know more about the kind of information that expert operators look for when trouble-shooting a rare fault. The literature states for quite a long time that experienced operators search for information that explains the symptoms most of the time and that their errors rely on this strategy. However, as far as we know, very few empirical data have been published. The other interest is related to accidents.

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[1] These tools are not necessary to locate the fault.

[2] A ring is a metallic seal around a piston.

[3] The obstruction of an intake tube is possible, especially when the engine is stripped down in order to repair it. The operator may leave behind a piece of cloth when reassembling engine parts together. Although it is possible, this occurrence is extremely rare.

Rare fault configurations are typically the kind of situations where experienced operators can exhibit erroneous behaviours. When this occurs during landing with a commercial aircraft (e.g. wheels-up landing of a DC9 at Houston; see National Transportation Safety Board, 1997), some of the symptoms may be neglected. Then, the problem can be left unsolved due to time pressure and there may be very serious consequences.

7.6. Instructions

The subjects first visually inspected the engine. This inspection allowed them to recognize the components of the engine that were in an unusual configuration (on a trailer). Then the instructions were read.

" I'd like you to trouble-shoot this engine. I will show you what the problem is when I have finished reading these instructions. This is not an evaluation of your skills. I only want to collect data on trouble-shooting. Your superiors will only anonymously be informed about the results of this study. Do you agree to take part in this work? "

If an operator refused, he was discarded from the experiment.

"In order to find what's wrong, you may use any tool from this toolbox (the experimenter pointed at the toolbox). *You cannot use any electronic diagnostic tool.*
Each time you make an operation, perform a measure etc., you must tell me the name of the component you are going to work on, what result you expect and what you might be able to deduce. If you do not deduce anything, you must tell me so. I am not a specialist in mechanics. Thus I would like you to explain to me what you are doing, so that I can understand.
You can use the technical book. You can consult it as often as you want.
Did you understand the instructions?
Do you have any question?"

Some subjects wanted to know more about the history and the age of the engine. The experimenter answered these questions for this is what occurs when professional mechanics work on an engine. No formal record was kept about the questions asked by the subjects. As a consequence, they will not be included in the experimental data.

7.7. Procedure

After the instructions were read to the subject, the task began. It ended when the subjects located the cause of the fault or when they gave up. The experimenter gave some pieces of advice (especially to novices) in order to protect the engine against possible damage.

7.8. Variables

There was one between-subjects variable: expertise.
The following variables point to elements of the engine that were likely to be investigated by the subjects, given the symptoms of vibration. As the cylinder #4 is the one that is malfunctioning, we focused some variables on this area of the engine. The initial set of raw variables (variables 1, 2, 4, 6, 8, 10) has been enriched with derivative variables. For the latter, percentages were computed to allow the comparison of raw values relatively to the total amount of operations. Thus, variables 3, 5, 7, 9, 11 are expressed as percentages of the total number of operations. These were calculated out of the data from each subject and then averaged.

1/ *Total number of operations*. For the purpose of this experiment, an operation was considered as any information acquisition process. It could be a test (measure, stripping, etc.) or checking out an external source of information (technical book).

2/ *Pulling out plug's cable #4*. Pulling a plug's cable while the engine was running allowed one to know whether the corresponding cylinder exploded or not. If the engine speed did not decline when the cable was pulled out, then the cylinder did not explode. It was important that subjects pulled out the cable of the cylinder #4 for it was the one that exhibited abnormal symptoms.

3/ *Percentage of pulling out plug's cable #4.*

4/ *Number of operations before pulling out any plug's cable.* This variable indicated how soon a cable was pulled out during the trouble-shooting process. The sooner the cable is pulled out, the more likely it is that the operator prioritises an electrical cause of the symptoms.

5/ *Percentage of operations before pulling out any plug's cable*.

6/ *Operations on cylinder #4*. This variable referred to the total number of operations performed on that cylinder.

7/ *Percentage of operations on cylinder #4.*

8/ *Electrical operations*. Electrical operations concerned components such as plug cables, high-tension module, etc.

9/ *Percentage of electrical operations.*

10/ *Mechanical operations.* Mechanical operations concerned components such as rocker arms.

11/ *Percentage of mechanical operations*.

One may object that the measures above are insufficient to perform a deep analysis of the operators' activity. However, in previous papers and with the same kind of dependent variables, Besnard and Bastien (1999) and Besnard (2000) recorded the plausibility of a heuristic rule-based reasoning process responsible for expert errors in electronics trouble-shooting. This is one piece of argument supporting our choice for the same kind of dependent variables.

7.9. Predictions

Novices do not directly match symptoms with causes. They first have to build a representation of the fault. As a consequence, we assumed they would need more information than experts in order to clearly define the symptoms. Thus we expected novices to perform more operations than experts (V1).

Experts implement strategies that save cognitive resources. As pulling a cable, from a cognitive perspective, is a cost-effective test and as the cylinder #4 exhibits abnormal symptoms, we expected experts to pull out cable #4 (V2 & V3) more often than novices. In the same way, the number of operations before pulling any cable (V4 & V5) should be very low among experts. The reason is that it is a way to test the most frequent cause of the symptoms exhibited by the engine.

The cylinder #4 exhibits abnormal symptoms. These symptoms (the main of which is vibration) imply a series of operations in this cylinder in order to test potential causes. As experts are expected to narrow down the set of possible faults more efficiently than the novices, we expected the latter to perform more operations on this cylinder (V6 & V7).

Most of the time, when a cylinder does not explode, the causes are electrical. Following our theoretical hypothesis of the implementation of a heuristic rule, we expected experts to perform more electrical operations (V8 & V9) than novices. However, we had no prediction about mechanical operations (V10 & V11). These two last variables may nevertheless provide some supplementary data.

8. Results

Only two subjects (experts) found the cause of the fault. Although experts exhibit the best performance regarding the final issue of the diagnosis (2/8 experts *vs.* 0/8 novices), one will see that the strategy they implement is generally founded on the knowledge of the frequency of the faults. In the current case, this is not the optimal strategy. This point will be discussed further.

The table 1 summarizes all the results. Figure 1 and figure 2 graphically display only the significant results. The analysis of variance shows a significant difference in the total number of operations performed by the two groups of subjects (F(1;14)=7.507; p=.015). As predicted, experts performed fewer operations than novices (10.7 *vs.* 17.3).

The percentage of pulling a cable shows a significant effect of expertise (F(1;14)=10.353; p=.006). As expected, experts proportionally used more this kind of test than novices (19 *vs.* 9.6).

Table 1 : Summary of the results

	Experts		Novices				
Variable	mean	sd	mean	sd	F	d.f.	*p*
1. total number of operations	10.7	5.2	17.3	4.4	7.507	1 ; 14	*.015*
2. pulling cable #4	2	0.9	1.5	1.2	0.875	1 ; 14	*.365*
3. % of pulling cable #4	19	0	9.6	0.1	10.353	1 ; 14	*.006*
4. operations before pulling a cable	0	0	3.6	4.6	5.059	1 ; 12	*.044*
5. % of op. before pulling a cable	0	0	24	0.3	5.653	1 ; 12	*.034*
6. operations on cylinder #4	3.7	1.7	3.2	1.4	0.4	1 ; 14	*.537*
7. % of operations on cylinder #4	34.7	0	18.1	0.1	14.68	1 ; 14	*.001*
8. electrical operations	8.5	3.5	12.1	3.8	3.815	1 ; 14	*.071*
9. % of electrical operations	81.9	0.1	75.5	0.3	0.28	1 ; 14	*.60*
10. mechanical operations	1.1	1.6	2.2	2.3	1.257	1 ; 14	*.281*
11. % of mechanical operations	10.7	0.1	15.1	0.1	0.28	1 ; 14	*.60*

- Variables 5 and 6 only show 12 d.f. as 2 novices produced no data on these variables.
- For each experimental subject, the variables expressed as percentages (3, 5, 7, 9 & 11) were calculated out of the raw data from variables 2, 4, 6, 8 and 10 respectively, in conjunction with the total number of operation of this subject. Then, an average value was calculated and displayed in this table. As a consequence, one must not expect, for instance, the "percentage of pulling cable #4" to be calculated out of the mean values of "pulling cable 4" and the "total number of operations". The mean values displayed in this table cannot allow one to perform such an operation as the percentages out of means are not equal to the mean of the percentages (displayed here).

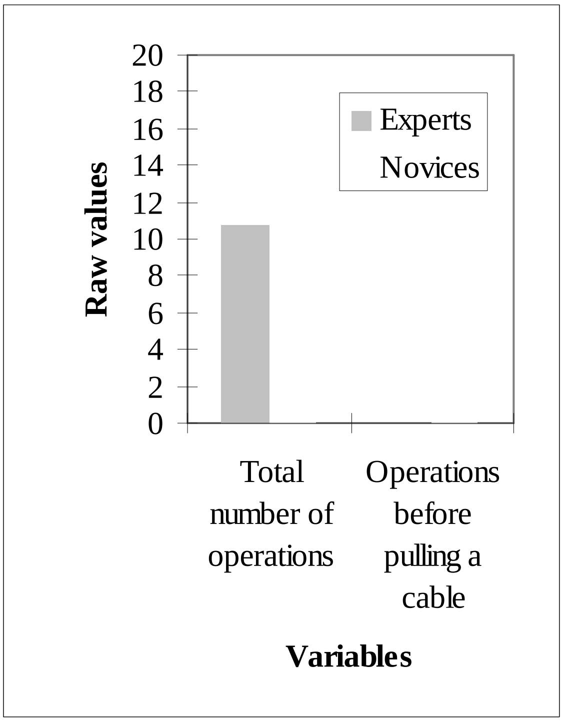

Figure 1: Total number of operations and operations before pulling a cable as a function of the level of expertise.

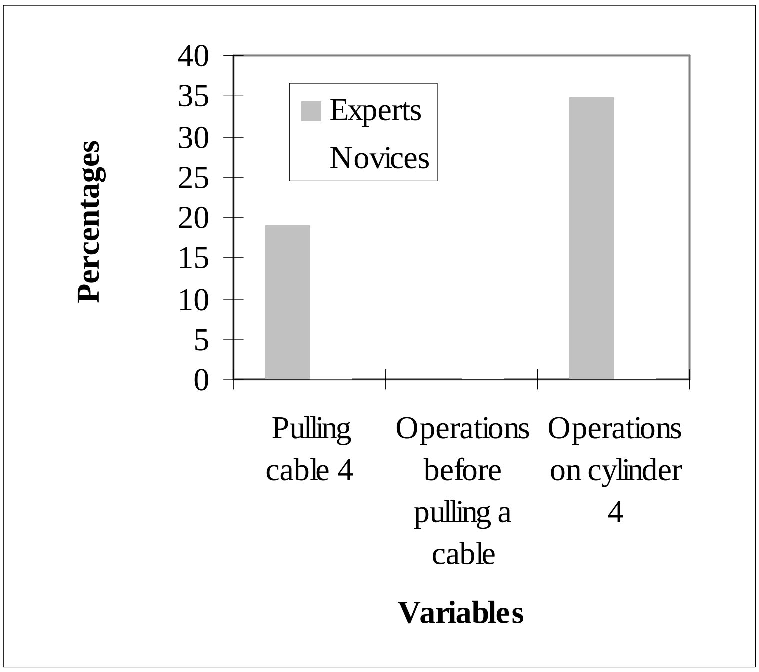

Figure 2: Percentage (in the total number of operations) of pulling cable #4, percentage of operations before pulling a cable and percentage of operations on cylinder #4 as a function of the level of expertise.

The number of operations before pulling out a cable significantly differed between experts and novices. Experts performed this test sooner than novices, both in terms of raw number of operations (0 *vs.* 3.6) (F(1;12)=5.059; p=.044) and in terms of percentage (0 *vs.* 24) (F(1;12)=5.653; p=.034). From this set of results, one can infer that pulling a cable is the test that is most often associated by experts with the current configuration of symptoms. To us, these data support our hypothesis of the implementation of a heuristic rule.

One can also see a significant effect of expertise on the percentage of operations on cylinder #4 (F(1;14)=14.68; p=.001). Experts proportionally performed more operations on that cylinder than novices (34.7 *vs.* 18.1). This result points up the fact that experts have correctly located the area where the symptoms originate.

Finally, the analysis of variance shows no significant effect on the number of times subjects pulled out cable #4, the operations on cylinder #4, the electrical operations and their percentage, and the mechanical operations and their percentage.

9. Discussion

Generally speaking, expert mechanics implement strategies that match symptoms with the most probable cause. First, these strategies try to assess whether the fault is a mechanical or an electrical one. When pulling cables, the operators try to locate the faulty cylinder by listening to the speed of the engine. If it does not decline when pulling a given cable, the corresponding cylinder is faulty. Then, operators must discover why the cylinder does not explode. The electrical causes can be withdrawn by making the plug #4 spark on the engine block, outside the combustion chamber. The operators can then deduce that the whole electrical circuit is working properly. Operators then search mechanical faults in the timing of the engine and/or in the play of the valves. Once controlled, operators evoke the airtightness of the cylinder #4[4]. This hypothesis, if tested, would imply stripping the engine down. For time reasons (several hours are needed), this was not allowed in the experiment. Moreover, this is not necessary to locate the fault.

Experts generally used the "pulling a cable" test sooner, they performed more operations on the cylinder #4 (in percentage) and they pulled out the cable #4 more often (in percentage) in the trouble-shooting process. Experts used the "pulling a cable" test very soon since most of the time, a cylinder that does not explode has an electrical problem. As a plug’s cable is at the end of the electric circuit, a spark means that every upstream electric component works properly. The power of this test probably explains why it was so rapidly used by experts. Experts performed more operations on the cylinder #4 (in percentage) because it showed the most salient symptoms. The operators, especially experts, knew that they had to investigate this area of the engine. Thus, as a first step interpretation, one could assume that experts behaved optimally when trying to implement a rule from surface features as this strategy is often fast and reliable. Moreover, the trouble-shooting process must start from some initial information. For reasons dealing with cognitive resources savings, this initial information has to be surface cues. Even if a given heuristic rule may trigger when all the conditions of implementation are not present, one must accept the idea that most of the time, this rule allows the experts to reach a high level of performance. But we believe that the experts (except the two who found the cause of the fault) analysed the fault in the engine on the sole basis of the surface cues. They have not been able to explain the symptoms otherwise than according to the most frequent causes. This rule-based explanation relies on the knowledge of frequency-distributed links between symptoms and causes that trigger hypotheses and tests from a pattern of features. If they actually had implemented a structure-based strategy

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[4] A cylinder that leaks lets the mixture escape outside the combustion chamber and does not explode.

(defended by Hardiman *et al.* 1989; Smith, 1992 and Zajchowski & Martin, 1993) on the basis of functional or topographical properties of the engine, they could have hypothesized that an obstruction had occurred. So that it can explode, a cylinder needs a high compression rate, a spark and a petrol/air mixture. If the operators had returned to this level of abstraction, they would probably have located the fault since they could have tested the possibility of the mixture not getting into the cylinder. The experimental data cannot support such a conclusion.

We now discuss the absence of significant results on the raw number of times subjects pulled out cable #4, the raw number of operations on cylinder #4, the electrical operations and their percentage, and the mechanical operations and their percentage. The number of times cable #4 was pulled was rather similar between experts (2) and novices (1.5). Obviously, that does not mean that they processed the same information in the same way. The absence of significant difference on this variable can be explained by a ceiling effect: Pulling this cable twice is enough to isolate this cylinder as the faulty one. However, when compared with the total number of tests, the two samples of subjects differed significantly (experts: 19 *vs.* novices: 9.6; p=.006). This difference provides some information about the relative weight of this operation to the whole trouble-shooting process. Our position is that comparing percentages makes sense as it takes into account part of the variability existing between two samples of subjects. Put in other words, 5 operations out of 10 on a given component and 5 operations out of 100 on the same component may not be based upon the same processes.

Electrical operations and their percentage as well as the mechanical operations and their percentage showed no significant differences, the absence of significant results on the electrical operations contradicting our predictions. One of the possible explanations is that the granularity of these variables was not adequate for exhibiting any difference between the two groups of subjects. Variables specifically dedicated to some electrical components and some mechanical components may have given more information.

As a total, five out of the nine predictions we proposed were not supported by the results. To us, the main cause is the imprecision of four of the above-mentioned variables. Even if the significant results support our theoretical hypothesis of a heuristic rule-based reasoning process responsible for expert errors, we are aware that further significant data would have enriched the discussion and provided a more solid basis for it.

10. Cognitive processes involved in trouble-shooting

Experts do have extended knowledge about engines. If asked to do so, they can reason from a fault towards its consequences. But in trouble-shooting, the reasoning process goes backwards from the consequences to the fault and heuristics are implemented in order to cope with complexity. The heuristic faultfinding process must then take a statistical risk in order to formulate a fault hypothesis. This risk relies on taking surface features into account while reasoning about a potential cause. A discrepancy between the symptoms and the usual cause may lead the subjects to not locate the fault. In our study, the application of a heuristic rule by the experts created a bias in the trouble-shooting process since the effects of the obstruction of the intake tube, which is an exceptional occurrence, were interpreted as the symptoms of a known fault.

Even if it would be expensive in time and resources, why do not experts use basic declarative knowledge -at least as a second step trouble-shooting strategy- in order to generate and test new fault hypotheses? According to us, the reason is that expert reasoning process becomes rigid with time. The knowledge used to solve problems (a set of rules) is organised so that the well-known cases can be processed efficiently. Progressively, the set of cases where a rule can be applied becomes more and more narrow until this rule is launched only when it is (supposed to be) relevant. Cognitive resources savings are the aim of this implicit selection process. Another feature of the rules is that they tend to exclude the use of the inferential reasoning mode. In other words, an operator produces little inferential reasoning when expertise is developed. A possible explanation is that inferences do not only need declarative knowledge. They also need an organisation of this knowledge that is adapted to this reasoning mode. With experience, the organisation no longer supports inferences as it was transformed to produce associations betweens faults and causes.

However, two of the experts successfully located the fault. Both performed a diagnosis based on the scenario described previously. They searched for a) electrical and b) mechanical causes. These two successful experts conformed to the classical test plan but thereafter noticed a difference in the colour of the seals of the intake manifold. The edge of the seal of the cylinder #4 was grey instead of red. This was the starting point for the test of the hypothesis of an improper seal obstructing the flux of the mixture towards the cylinder. We assume that these two experts noticed this difference in colour because they had abandoned a frequency-based set of hypotheses, allowing them to integrate new information as potential fault causes. The rule-based level of control may not be the proper one to identify relevant cues in an atypical problem. At this level of control, the same kind of information may be searched repeatedly, leading to a fixation error.

10.1. Auto-evaluative behaviour

Some operations concerned engine timing, carburettor and high tension (HT) of the electrical circuit. In the kind of fault studied here, it is no use testing these functions for they have equal effects on the four cylinders. If one assumes that sub-optimality is the nature of a hypothesis that does not allow one to acquire any information about the cause of a fault, then we can state that some of the operators have behaved sub-optimally. This was the case for 2 experts and 5 novices. Nevertheless, a very important difference between the two samples of subjects is that experts rejected the hypothesis before testing it. For instance, the expert #7said that *"the fault could be on the carburettor but… no, it is not possible. The three other cylinders would not work properly whereas they actually do."* Novices did not exhibit such an auto-evaluative behaviour about their own hypotheses. Another instance of this phenomenon led the expert #4 to reject the hypothesis of an obstruction of the intake tube #4: *"There could be a problem with the intake being obstructed...but it cannot be because the spark plug is wet."* These two examples account, at least for two subjects, for a meta-analytic process. Under the condition that they are able to talk while working, subjects can provide some cues about the content of the mental simulation going on during the trouble-shooting.

10.2. Misperception of symptoms

Although they have the greatest amount of experience of the two samples, some experts misperceived environmental features. Six out of eight experts verbally expressed what they had perceived from the spark plug #4 once stripped down. Four of them asserted that the plug was wet due to unburned petrol. The two others asserted that the plug was greasy due to some oil entering the cylinder, which was correct. In the case of the fault we implemented, the quality of extraction of this particular symptom had no systematic effect on the outcome of the trouble-shooting: one of the experts who asserted seeing petrol on the plug finally found the obstruction plate. Nonetheless, misperceiving the nature of symptoms is not always without consequences. When this occurs in dynamic situations, it can cause serious accidents to occur. The Three Mile Island accident (Kemeny, 1981) and the crash of a B737 at Kegworth (Ladkin, 1996) were partly caused by errors of interpretation or reading of the information displayed by the system.

11. Limits of the study

We have considered our experienced mechanics as experts. From our point of view, if operators can implement a frequency-based diagnosis and perform rule-based actions, then we assume that these operators are experts. These behaviours are typical of expertise as they rely on a re-organization of knowledge according to goals such as reliability, cognitive resources savings and processing speed**.**

Experts have implemented a frequency-based diagnosis and performed actions linked with a rule-based level of control. However, the criterion we have chosen in order to qualify our experienced subjects as experts can be put in question, especially if one takes into account the small number of years of experience of some subjects (10 years).

A second limit concerns the variables used as measures of the activity. The latter were chosen for their macroscopic nature. As a consequence, the level of detail provided by the data is rather rough. However, we only aimed at validating a general hypothesis in a field of research (natural trouble-shooting) where few quantitative data exist.

As a third limit, one cannot omit that experts' heuristics, most of the time, support a high-level of performance. The results we obtained in this study must not to be considered as representative of experts' usual activities since the subjects were artificially placed in a situation where an efficient behaviour has generated an atypical level of performance.

Finally, even if the experimental design intended to be as close as possible to ecological conditions of work, we have to admit that the cause of the fault in the engine (an aluminium plate obstructing the intake tube #4) is an artificial one. However, our choice for the fault was inspired by an actual cause: a piece of cleaning cloth left behind while re-assembling after the engine has been stripped down. The point is that a piece of cloth could have moved during the weeks of the experimental phase of our study whereas it is not an issue for a single operator working on an engine for only some hours.

12. Conclusion

We have experimentally studied experts' trouble-shooting strategies on a rare fault. The experimental device was a running engine and the conditions of the experiment were close to the ecological ones (same workshop, same tools, running engine). We have shown that experts involved in a trouble-shooting task implement heuristics on the basis of surface cues. This behaviour over-values the weight of some of the symptoms. This over-valuing is supported by a rule that leads to an automated launch of procedures. The situational cues are used to activate these procedures. The symptoms are linked with a frequency-distributed set of fault causes. When well-known symptoms are detected, then frequency-based rules may apply without always leading the subjects to locate the fault.

In Besnard & Bastien-Toniazzo (1999) and Besnard (2000), a rare fault was implemented in an electronic circuit and the frequency heuristic led the experts to test a valid integrated circuit (IC386) soon and often. In the present study, pulling out a cable is a crucial test for it may withdraw a great number of potential faults. It seems that a community of cross-field trouble-shooting strategies and errors exists. At least in technical domains, the frequency of the symptoms may be a major cue in the selection of the fault-finding procedures. After a similar proposition by Reason (1990) and empirical evidence among electronics operators, we may have found one more piece of (empirical) evidence about the plausibility of such a phenomenon.

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