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Cognitive flexibility and adaptability to environmental changes in dynamic complex problem-solving tasks

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People who show good performance in dynamic complex problem-solving tasks can also make errors. Theories of human error fail to fully explain when and why good performers err. Some theories would predict that these errors are to some extent the consequence of the difficulties that people have in adapting to new and unexpected environmental conditions. However, such theories cannot explain why some new conditions lead to error, while others do not. There are also some theories that defend the notion that good performers are more cognitively flexible and better able to adapt to new environmental conditions. However, the fact is that they sometimes make errors when they face those new conditions. This paper describes one experiment and a research methodology designed to test the hypothesis that when people use a problem-solving strategy, their performance is only affected by those conditions which are relevant to that particular strategy. This hypothesis is derived from theories that explain human performance based on the interaction between cognitive mechanisms and environment.

1. Introduction

It can be surprising that an observed person, considered under many criteria as an expert, and with many years of experience at performing a task, makes an unexplainable error. This situation has been described in many accident reports and the consequences of such errors are so important that for many years researchers have been trying to find an explanation for it.

A review of the literature shows that research conducted to explain this effect belongs to two related but different areas, *human errors* in *cognitive ergonomics* and *cognitive flexibility* in *cognitive psychology*. In both areas, despite the differences in background, and theoretical and methodological traditions, most researchers seem to believe that an unexpected change in the environment is the crucial factor when observing a drop in performance after extensive practice of a task. However, this idea has not been unanimously accepted.

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In cognitive ergonomics, most psychological theories (i.e. Norman 1981, Norman and Shallice 1980, Rasmussen 1983, Reason 1990, Hollnagel 1998) propose that human errors share certain characteristics, namely: (1) people lose conscious control when they increase their ability at performing a task; (2) there is a hierarchical structure (schemas, semantic networks or control levels) in which higher levels include, organize and control lower levels; (3) practice and elaboration lead to a representation which hides the process details that can lead to a lack of flexibility; and (4) there is a trade-off between quick, fluid actions and controlled, flexible actions.

These psychological theories would agree on the idea that in order to avoid human error, an individual needs to realize that the situation has changed in order to be able to 'log out' of the automatic processing mode and come into the controlled processing mode. To detect the situation change and the necessity of a non-routine response, it is necessary to come into a higher level of attentional control, where the individual accesses the new situation and plans the action to be taken. They need to perceive the environmental cues in a different way, reinterpreting them. How the person represents the task and the set of strategies employed to deal with it determines how easily she or he will shift attention to the new environmental conditions.

For example, Rasmussen (1983) proposed a taxonomy of human behaviour that can be used to frame this idea. He distinguished three levels or categories of human behaviour: (1) skill-based level, for activities done in an automatic way; (2) rule-based level, for situations in which our experience give us a response in a known situation; and (3) knowledge-based level, for new situations in which there are no rules and the individual needs to plan a different response. Within this framework, practice in a task leads to more automatic activities at the rule- and skill-based levels. However, when the task conditions change, a person must carry out activities accomplished at the knowledge-based level to adapt to those new conditions. In general, when a person knows that she or he is skilful, they are less prone to change her or his strategy after detecting the changes and/or they are less able to detect them in the first place. Then, for example, when experts rely on automated performance routines, they are less able to judge the likelihood of a failure in a system (Edland *et al*. 2000).

The problem with these theories is that they do not make any assumptions about which environmental changes would affect performance once a person has automated her or his performance, and implicitly assume that any change would do. That is, the only important factor for determining the drop in performance is the degree of automatization of behaviour. This explanation appears to be insufficient because in their interactions with the environment, experts are exposed to a huge variety of changes, and their performance is negatively affected only by some of them. Therefore, for the psychological theories above, it remains to be explained which environmental changes would affect performance and when.

Interestingly, in cognitive psychology researchers seem to disagree about the basic effect of environmental changes. On one hand, some researchers assume that experts have problems adapting to environmental changes and have explained this problem much in the same ways as did researchers in cognitive ergonomics. These researchers would share the idea that experts are less cognitively flexible than novices, and, indeed, empirical research has shown that inflexibility and expertise are intrinsically united (Adelson 1984, Frensch and

Sternberg 1989) and that experts change their mental representations of tasks less often than novices (Anzai and Yokoyama 1984).

On the other hand, some authors in cognitive psychology defend the opposite hypothesis and have problems explaining the effect. For example, the research conducted by Spiro *et al.* (1991) suggested that a characteristic of experts is that their multifaceted mental representations permit a better adjustment to the changes and a greater knowledge transfer between tasks. Reder and Schunn (1999) have found that the participants that performed better in a dynamic task differed from those with worse performance in their capacity to adapt their strategies to the changes in the conditions of the tasks, and not in the repertoire of strategies nor in their ability to execute a particular strategy.

A review of the research conducted by cognitive psychologists reveals the following unanswered questions: does the performance of an expert drop when the environment changes or not? If this conflict is solved by future research favouring theories that postulate the 'cognitive inflexibility hypothesis', it will remain to be explained which environmental changes would affect performance and when. If, on the contrary, Spiro's theory is true and experts are indeed more flexible than novices, it must be explained why experts can be observed making errors in situations that are very familiar to them, and in which they usually perform perfectly.

To solve this theoretical and practical issue it is tempting as researchers to follow in the tradition of cognitive psychology and try to design one or several experiments to decide who is right and who is wrong. To be successful such experiments would need to show results that could be interpreted dichotomically as supporting the conclusion that experts are more cognitively flexible or more cognitively inflexible than novices. However, it is possible that this research strategy is inappropriate because the real situation is that experts are not always flexible or inflexible, and they might be affected by some environmental changes but not by others. What needs to be investigated is which environmental changes affect expert performance and why.

This paper proposes an explanation that may provide answers to these questions and synthesize the different theoretical postures proposed up to now. The authors believe that previous theories have failed and have even predicted opposed effects, because they looked for explanations based only on cognitive mechanisms and did not consider the characteristics of the environment in which a person acts. The hypothesis is that only those changes that are important for the particular strategy that the person has developed during learning would affect her or his performance. To test this hypothesis it was necessary to develop a research methodology that is in many respects different from the traditional strategy used in cognitive psychology. However, before going into explaining the hypothesis and research methodology, the ecological theory of expertise by Vicente and Wang (1998) known as the Constraint Attunement Hypothesis (CAH), needs to be considered as a context. Briefly, this theory proposes that the acquisition of skills should be understood as the adaptation to the constraints imposed by the environment. People develop different strategies to adapt to those constraints, and each strategy would depend on different characteristics of the environment. Therefore, only those changes that affect the particular strategy a person is using would affect her or his performance.

Vicente and Wang (1998) suggest that cognitive theories such as Long-term Working Memory (LTWM, Ericsson and Kintsch 1995) and Elementary Perceiver and Memorizer (EPAM, Feigenbaum and Simon 1984) are insufficient to explain expertise advantage because they are process theories. Process theories attempt to explain only the cognitive mechanisms responsible for the behaviour. Thus, a process theory would offer explanations of why experts are better performers than novices based only on the cognitive process involved in the area of expertise. For more discussion about the importance of process theories versus product theories, see Ericsson *et al.* (2000), Simon and Gobet (2000) and Vicente (2000).

The CAH has been proposed to explain three related issues: (1) How should the constraints that the environment places on expertise be represented?; (2) Under what conditions will there be an expertise advantage?; and (3) What determines the magnitude of that advantage? Therefore, this is a product theory rather than a theory of processes. It is not examining which processes are responsible for a particular performance, but rather the conditions necessary for a given performance to be observed. It is also examining what determines the magnitude of the performance. Hence it is a theory that can help to explain this phenomenon of cognitive flexibility. Within its framework the question has to be reformulated and as a result, the focus is not the processes responsible for the declivity of performance, but which environmental constraints, in combination with which process, would determine when performance drops.

According to this theory, therefore, in order to completely explain the expert advantage a theory of the environment is also needed, that would allow predictions as to the conditions under which expert advantage would be observed. In order to investigate the question at hand, i.e. what characteristics of the environment must change so that the effect on expert performance may be observed, it is also necessary to have a theory of the environment that, together with the processes theory, explains the interaction between environment and processes.

In the experiment described here the participants learnt to perform a microworld task (also called complex problem-solving tasks). The conditions in the task remained constant for some time and participants had the opportunity to develop strategies to deal with them. At one point, those conditions changed and the effect of that change on performance was observed. Based on previous research, two components of the system relevant to two strategies that people usually employ in this task were selected and changed.

It was predicted that, in line with the CAH, there would be an interaction between cognitive mechanisms and environment, so that the environmental changes would affect performance depending on the particular strategy people develop. In any problem-solving task people develop strategies that allow them to perform within the constraints of the environment in which they have to behave. Learning means an adjustment to those constraints. However, there are many strategies that people could develop that would allow them to deal with environmental constraints in different ways but with the same efficiency. There are many constraints in any complex environment and each strategy would deal with one set of them. Therefore, when something in the environment changes, there could be strategies that allow participants to keep a good performance level in spite of the change, while other strategies will prevent them adapting to the new situation.

To test the hypothesis, an experiment was designed according to the following research strategy: (1) Perform an analysis of possible problem-solving strategies; (2) Perform a cognitive task analysis of the dynamic system; and (3) Select particular functions of the system that would affect subjects' strategies after performing a cognitive task analysis of the system.

1.1. *An analysis of possible problem solving strategies*

In the area of traditional problem solving, where a limited problem space exists, there is a usually well-defined goal and only one way of reaching the goal in the smallest number of steps. Thus, it is relatively easy to identify the strategies that a person will adopt. However, in the most complex problem-solving tasks, this identification is more difficult since an optimum strategy does not exist. Furthermore, the protocols of the participant can be so wide in data that they are probably produced by more than one simple strategy at the same time (Howie and Vicente 1998).

For this reason, a method of analysis was devised to identify the strategy adopted by the participants in our experiments, which has already proved to be useful (Quesada *et al.* 2000). Briefly, the method consists of comparing a participant's behaviour with that of a simulated participant adopting an hypothetical strategy.

Participants in these experiments learnt to extinguish fires in Firechief (see figure 1), a microworld generation program created by Omodei and Wearing (1995). Microworlds are complex problem-solving tasks and are an appropriate research environment to test the present hypotheses. Microworlds are based on simulations of tasks which change dynamically and are designed to reproduce the important characteristics of the real situations (the state of the problem changes autonomously as a consequence of the actions of the participant and the decisions must be taken in real time) but allow for the possibility of manipulation and experimental control.

In Firechief, participants utilize a screen that simulates a forest through which a fire is spreading. Their task is to extinguish the fire as soon as possible. In order to do so, they can use helicopters and trucks (each one with particular characteristics), which can be controlled by mouse movements and key presses. The different cells (see figure 1) have different ratings of flammability and value: houses are more valuable than forests, for example. The participant's mission is to save as much forest as possible, to preserve the most valuable cells and prevent the trucks from being burnt. Helicopters move faster and drop more water than trucks, but the latter can make control fires. Trucks are unable to extinguish certain fires, and they will be destroyed if they are sent to them. The fire is more intense and spreads faster depending on the wind direction. Participants can see a window with their overall performance score at the end of a trial, which is calculated adding every safe cell and subtracting the value of the burnt trucks. The task is complex and participants can feel interested from the beginning to the end. At the same time, it is possible to experimentally control features of the system, and to prepare experimental situations for testing a wide variety of hypotheses.

There are four commands that are used to control the movement and functions of the appliances: (1) drop water on the current landscape; (2) start a control fire (trucks only) on the current landscape segment; (3) move an appliance to a specified landscape segment; (4) search in a specified portion of the total landscape area. Only the first three commands were available in the present experiment. Thus, participants were allowed to move appliances, drop water and start control fires. Commands are given using a 'drag-and-drop' philosophy by first selecting the desired vehicle (by moving the mouse cursor into the landscape segment containing it) and then pressing a key on the keyboard. At the end of each trial, the program saves the command sequence that the participant issued in that trial.

The protocol output by Firechief at the end of each trial contained the sequence of commands that a participant issued during that trial (i.e. move a truck, drop water).

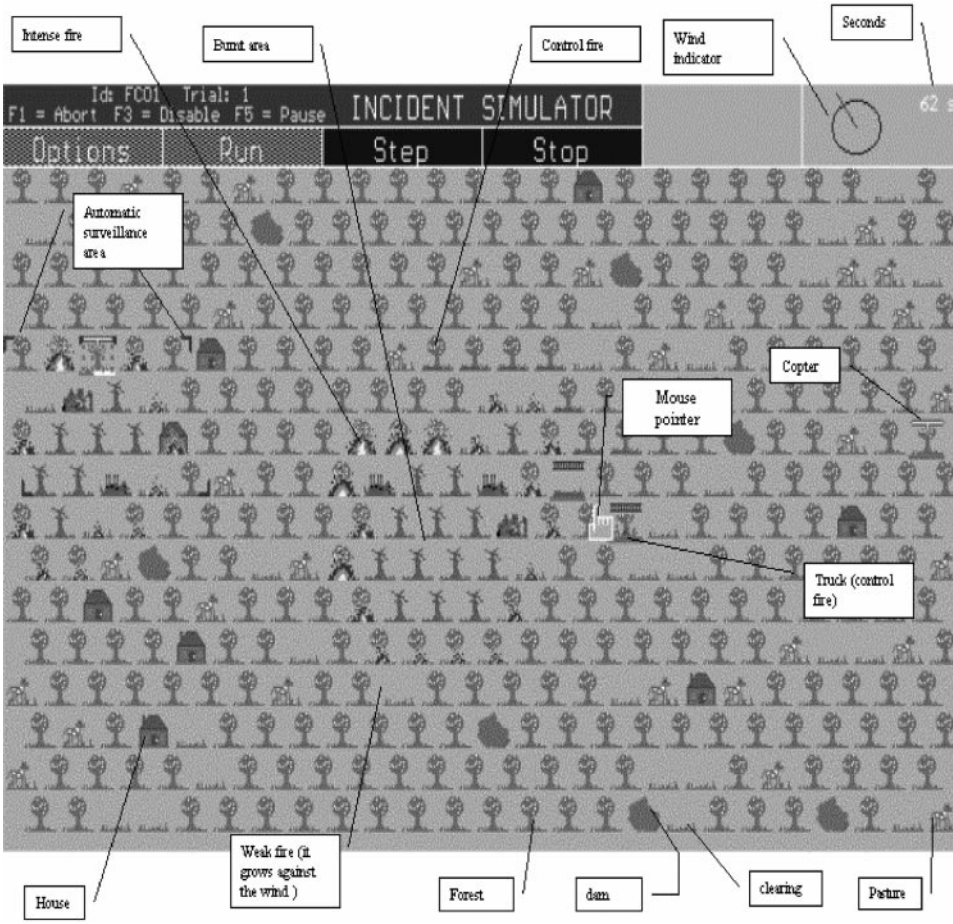

Figure 1. Screenshot of Firechief (Omodei and Wearing 1993).

From this sequence of commands it was hoped that a participant's strategy could be inferred.

One way to approach the analysis of strategies could be by counting the number of commands issued by the participant in the trial. It can be assumed that where two participants issue different commands, they must be using different strategies. However, this type of analysis, although simple, is also incomplete. There is more to participant strategies than could be detected just by counting the number of times each command is used. To illustrate this point, a hypothetical example with two participants can be considered. Table 1a presents the sequences of commands they issued. To make things easier, a simplified situation can be imagined where only two commands are available, *move* and *drop water* (see Omodei and Wearing 1995 for a complete description). Just by counting the command frequencies (see table 1b) it could be inferred that participants 'a' and 'b' seem to use a similar strategy based on moving appliances and dropping water on the burning fires the same number of times.

However, this analysis is insufficient and misses important information about participants' strategies, as can be seen when the particular sequence of commands is

Table 1. Example with sequences of commands issued by two hypothetical participants.
(a)

Time	Participant a	Participant b
t1	Move	Move
t2	Drop	Move
t3	Move	Move
t4	Drop	Move
t5	Move	Drop
t6	Drop	Drop
t7	Move	Drop
t8	Drop	Drop
t9	Move	Move
t10	Drop	Drop
t11	Move	Move
t12	Drop	Move
t13	Move	Drop
t14	Drop	Drop
t15	Move	Move
t16	Drop	Move
t17	Move	Drop
t18	Drop	Drop
t19	Move	Move
t20	Drop	Drop

(b)

	No. of Move commands	No. of Drop water commands
Participant a	10	9
Participant b	10	9

(c)

	Move	Drop water
Participant a		
Move	0	10
Drop water	9	0
Participant b		
Move	5	5
Drop water	4	5

examined. Participant 'a' seems to be using a strategy that consists of moving an appliance and then using it to drop water. However, participant 'b' seems to be engaged in a strategy by which she or he compulsively issues the same command several times in a row. Therefore, the method required is one which captures the sequential information and allows an analysis of problem-solving strategies. Such a method could be based on counting the number of times a command is issued following another command, as has been suggested by Howie and Vicente (1998). These authors showed that the sequence of commands in the participant's protocol could be used to construct a matrix of transitions between actions (see table 1c). Rows and columns in the matrix represent the command and the cells contain the number of times that one command follows another. This matrix contains important information about problem-solving strategies since transitions between actions reflect how a person issues the commands (Howie and Vicente 1998). Therefore, the method for inferring participants' strategies is based on the analysis of matrices of transitions between actions and is carried out as follows:

1.1.1. *Construct empirical matrices of transitions between actions*: For each trial of each participant, a protocol file was obtained in which all the actions were registered, in a temporal sequence. Then, every transition between two actions was extracted, and put in an asymmetrical square matrix of size equal to the number of possible actions.

1.1.2. *Design a set of theoretical, simple strategies based on a task analysis*: Any method of analysis proposed to study problem-solving strategies must allow the researcher to test hypotheses based on theories. Therefore, the next step proposed tests a set of theoretical strategies that allow the identification of each participant's actual strategy, indicating a theoretical model of the cognitive processes involved in complex problem solving in dynamic tasks.

The Firechief program has a simulation module that allows the implementation of problem-solving strategies. This module uses Pascal code, and provides a function library to facilitate the design of those strategies. When recompiled, the simulation module takes the programmed strategy and accomplishes the task as would a participant who adopts it. Therefore, the program generates the equivalent protocol files to those that would be generated when a human participant accomplished the task. That is to say, a protocol can be obtained from a simulated participant that has performed the task with a single hypothetical strategy. From this protocol it is possible to obtain a matrix of transitions between actions.

Based on our previous research (Quesada *et al.* 2000), two possible strategies that participants might be using have been devised:

Move and drop water (MOVE-DROP): According to this strategy, the participant moves appliances to the closest unattended fires and drops water there. Trucks are not sent to fires that are too fierce and where they could be destroyed.

Control fires (CONTROL): This strategy can only be used by trucks. It involves finding the closest fire and then sending an appliance to deliberately light small fires in a location two segments away from it in a randomly chosen direction. Before that, the algorithm checks that the location is unoccupied and not burning or already burnt.

These strategies were simple, easily distinguished and orthogonal in the sense that the matrices of transitions generated by them did not correlate. They do not represent a theory of complex problem solving, but they are sufficient for the purpose of this experiment and, more importantly, they allow a demonstration of the validity of the research procedure.

1.1.3. *Correlate empirical and theoretical matrices*: When the theoretical matrices were introduced as predictors of the matrix of transitions between actions of one participant, it was possible to identify which one of them was used by her or him. Then, to evaluate the possibility that one participant had used one particular strategy, the similarity between her or his empirical matrix and that obtained from simulating the strategy was calculated. A significant correlation between those two matrices means that, to some extent, that strategy was responsible for her or his performance. Therefore, the matrices were converted into vectors and a multiple regression analysis was performed with the empirical matrix as the dependent variable and the simulated strategies as the predictors. The betas in the analysis represented the partial correlation between the strategies and the performance of the participant. For example, if one participant adopted the MOVE-DROP and CONTROL strategies in one trial, significant ($\alpha = 0.05$) betas for the matrices representing these strategies (see figure 2) would be found.

1.1.4. *Classify participants according to which strategy they used*: A rectangular matrix was built representing each participant's similarities with the theoretical strategies. Rows represented the participants and columns represented the strategies. One cell in the matrix had a value of one if that participant used the corresponding strategy. As can be seen in table 2, one particular participant might have used one or two strategies. Finally, a cluster analysis was performed on that matrix to group participants with similar strategies.

Therefore, the result of this method is a classification of participants into groups based on the similarity of their strategies. This grouping could be used as a quasi-experimental independent variable in a factorial design to evaluate its interaction with other manipulated independent variables.

1.2. *Cognitive task analysis of the dynamics of the system*

Following this line of reasoning, the next step is to describe the constraints imposed by the environment. The advantage of using the microworld approach is that the environment is generated in laboratory conditions, and the constraints are formally defined. In this experiment, all the conditions (the initial state) in the system are set

$$\underset{\text{Empirical Matrix}}{\begin{pmatrix} x_{11} & x_{12} & \cdots \\ x_{21} & x_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}} = \beta_1 \underset{\text{Theorical Matrix Strategy 1}}{\begin{pmatrix} a_{11} & a_{12} & \cdots \\ a_{21} & a_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}} + \beta_2 \underset{\text{Theorical Matrix Strategy 2}}{\begin{pmatrix} b_{11} & b_{12} & \cdots \\ b_{21} & b_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}} + \ldots + \beta_z \underset{\text{Theorical Matrix Strategy z}}{\begin{pmatrix} z_{11} & z_{12} & \cdots \\ z_{21} & z_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}} + \epsilon$$

Figure 2. Regression equation with matrices of transitions between actions.

Table 2. Matrix of participants by strategies. Each cell in the matrix represents the one strategy being used by one participant. A value of 1 means a significant beta in the regression analysis. A value of 0 means a nonsignificant beta.

	Strategy 1	Strategy 2
Participant 1	1	1
Participant 2	0	1
Participant 3	1	1
⋮	⋮	⋮

to be the same for all participants and for all trials, generating an environment particularly suitable for fast learning of the dynamic system. Nevertheless, given the inner dynamics that these complex systems show, two trials are not necessarily the same even if the initial state was identical (see Omodei and Wearing 1995).

Vicente and Wang (1998) and Vicente (2000) use an abstraction hierarchy first proposed by Rasmussen (1986) to perform cognitive task analysis and identify the goal-relevant constraints in a particular problem domain. An abstraction hierarchy is, among other things, a framework for identifying the multiple levels of constraints that are presented in a physical system. The abstraction hierarchy is the main contribution of CAH to the expertise literature (Vicente 2000) and functions as a description tool for environments. The details of different models of the environment usually differ tremendously from one domain to another because the relevant cues and their ecological validities can change tremendously. But if a common theory of the environment is used, these models remains comparable.

However, for the present purpose it was not necessary to perform a complete abstraction hierarchy and a more simple analysis allowed an identification of the constraints relevant for each strategy. Moreover, CAH has been criticized since it requires constraints to be constructed and rationalized *ad hoc* for each task (Simon and Gobet 2000), and is far from a computational, formal model of the environment. The present endeavour describes only the formal characteristics of the system, as well as the important parameters acting upon the user's view, and tries to impose as few *ad hoc* assumptions as possible.

There are two types of components in Firechief: (1) Components controlled by the system (fires, landscape segments, wind, etc.); and (2) Components controlled by the user (appliances: truck and helicopters). This section describes them, as well as the cognitive demands associated with each theoretical strategy that the analysis proposed.

The behaviour of the components controlled by the system depends on the functions governing the spreading of fires. Using those functions, the Firechief program uses a two-part model for specifying the development of incidents: one part of the model specifies the behaviour of fires within a screen segment and another part specifies how fire spreads to adjacent screen segments. These equations are:

(1) Fire intensity (F)

$$\mathrm{Fij} = \mathrm{Dix} \times \mathrm{Bij} \times \mathrm{Ra}\ (.4 + \mathrm{e}(\mathrm{Wij} + \mathrm{Hij})\mathrm{InS}) - \mathrm{Mij} \quad (1)$$

where Dij = Density in landscape segment ij; Bij = Build up factor for fire in landscape segment ij; Ra = Fire spread rate in landscape segment of type a; Wij = Wind direction factor for landscape segment ij; Hij = Headfire adjustment factor for landscape segment ij; S = Wind strength; Mij = Water moisture content in landscape segment ij; and

(2) Combustible fuel

$$\mathrm{Cij}\ (\mathrm{t}) = \mathrm{Cij}\ (\mathrm{t\text{-}1}) - \mathrm{Fij} \times \mathrm{g} \quad (2)$$

where Cij(t) = Combustible fuel in landscape segment ij at yime t; Cij (t-1) = Combustible fuel in landscape segment ij at yime t-1; Fij = Fire intensity in landscape segment ij; G = Length of simulation time unit.

These two functions estimate the current fire intensity in each screen segment (Fire Intensity), the amount of combustible fuel in the segment during the simulated time unit and the estimated amount of combustible fuel that remains (Combustible Fuel).

When the total amount of combustible fuel in a screen segment falls below a minimum specified value, the screen segment is declared destroyed and any adjacent combustible screen segment is declared ignited.

Of course, the user does not learn of these formal details. When she or he interacts with the system, a set of epistemological characteristics emerges, based on these formal constraints. For example, the user sees that fires are bigger in the direction the wind is blowing; she or he notices that the fire is spreading faster in certain types of cell than in others; the fire is not able to burn a cell where the humidity is high (because water has been dropped on it even though there was no fire); etc.

The more important characteristics of the system that affect the user controlled components are:

(1) 'Appliance efficiency': The capacity of helicopters and trucks to extinguish fires by dropping water. Both appliances have a maximum fire intensity value beyond which they are not able extinguish the fire. This value is lower for trucks.
(2) 'Drop/fill time': Length of time which an appliance takes to drop or fill with water.
(3) 'Control fire time': In these simulations, the time needed to create a control fire is equal to the time needed to extinguish a fire by dropping water over it.
(4) 'Relative Appliance speed': Speed at which the appliances move.
(5) 'Lost truck value'. Trucks can get burnt if sent to a fire bigger than they can extinguish. They normally warn the user with an alarm tone. This feature makes using trucks risky, because a burnt truck makes the user performance value drop down rapidly.
(6) Number of appliances.

To develop a strategy, participants have to assign a 'utility value' to every system feature where they can act upon and evaluate how they are affected by all the other system features that they cannot manipulate. For example, provided that a participant has two helicopters and two trucks, trucks are slower, trucks are able to make control fires but can be burnt while trying, and the cost of burning a truck is X, should a participant use trucks more than helicopters?

It is more than likely that participants develop and use several strategies. The important point here is that they need to decide which strategy to use, and more importantly, do they stick to it when conditions change. For example, they have to decide whether to use control fires or water, where to put the control fires, whether they are going to focus on the helicopters or trucks, and evaluate the importance of burning a truck, etc. In cognitive terms, this means that people interacting with Firechief are learning to predict future states of the system governed by these equations, although this does not imply that they know the formal characteristics of the system.

MOVE-DROP strategy demands: To put out a fire by dropping water, participants have to locate a fire, move an appliance to it and press a key. In implementing this strategy, the algorithm selects the fire to move according to two criteria: the nearest fire plus the most intense fire. It is assumed that people select the most intense fire first because it is the one with the highest probability of spreading in the near future, and therefore it is the most important fire to extinguish.

To successfully put out a fire, the user must know the dropping water power limit for each appliance, and the relationship of fire size and fire intensity. Then, the participant has to compare both and decide if it is safe to proceed in sending the truck to the fire. If this comparison is not performed, the user could send a truck to a big fire and end up losing the truck. Participants then need to learn the maximum fire size that a truck can afford, and avoid sending a truck to fires exceeding this size. The theoretical strategy MOVE-DROP, which implements these operations, remembers the size of the last fire where a truck was burnt, and does not send any other truck to fires equal to or bigger than this one. This strategy is primarily stimuli-driven.

CONTROL strategy demands: To create a control fire, the user has to move a truck to a position in the screen where she or he thinks that the fire will be spreading in the next few seconds. It cannot be too near the fire, because otherwise the advancing fire will invade their cell and ruin their control fire. Once there, they have to press a key and wait (without moving the truck) until the control fire is finished. Moving the truck before the control fire has ended results in a provoked fire. All these features are represented in the theoretical strategy CONTROL as well. This makes the control fire strategy cognitively more demanding than the MOVE-DROP strategy.

The CONTROL strategy implies a prediction as to where the fire will be in the next few generations. Additionally, it implies having an approximate idea about the velocity at which the fire will be spreading, because the participants need to guess the position of the fire to avoid being attacked while the truck is performing the control fire. As Brehmer and Dörner (1993) have stated, people have difficulties in understanding the regularities in the time-course of events when they receive the information about these regularities in the form of isolated events over the time. At the same time, programming shortcomings impedes the implementation of this prediction component in the theoretical strategy. The libraries included in the Firechief simulation module do not contain any function to obtain information about wind direction and/or fire spreading time constraints. Therefore, the assumption is that people have difficulty in understanding the time regularities. In this strategy the prediction component is more important than in the MOVE-DROP strategy.

1.3. *Changes in those aspects of the environment that would affect the particular strategies that people adopt to solve the task*

Selecting particular functions of the systems that would affect subjects' strategies requires analysis of what each particular strategy means in terms of the components of the system. In this sense, it can be seen that the CONTROL strategy depends fundamentally on the wind direction. A person who is using this strategy must predict in which direction the fire will extend in order to make the control fire in that direction. The direction in which the fire is spreading depends, among other things, on the direction of the wind. Therefore, among all the environmental stimuli available in Firechief, the direction of the wind will be very important for participants using the control fire strategy.

The strategy of moving and dropping water depends, among other things, on the efficiency with which the trucks and the helicopters drop water. More efficient appliances would lead to strategies that move them less often than less efficient ones. The parameter setting 'Appliance efficiency' controls the capacity of helicopters and trucks to extinguish fires. The value of this setting specifies the maximum fire intensity at which both appliances are capable of extinguishing fires.

Therefore, these could be two parameters that would affect the two strategies expected in the experiment in different ways. On one hand, the wind direction would affect the strategy of creating control fires. If the wind suddenly changes direction, the participant would have to set the control fire in different locations, and more importantly, it would be more difficult to make predictions of where the fires will spread. However, this parameter would not affect participants using the strategy of moving and dropping water, whose only concern is related to the location of the fire in order to move their appliances there. On the other hand, the appliance efficiency would affect only the move and drop water strategy: Participants who rely mainly on the helicopters' greater water dropping power to put out the biggest fires will be severely hampered by this manipulation. When diminished, the trucks' lower water dropping power makes them an almost useless resource. Setting control fires does not depend on how efficient the appliance is at dropping water, so participants who were using the control fire strategy or those who changed to it would not experience any performance drop.

2. Method

2.1. *Participants*

Eighty-four students at the University of Granada participated in the experiment as part of class requirement.

2.2. *Procedure*

Participants were asked to undertake 22 trials, where 16 of them had constant conditions and the last six had variable conditions: the wind changed from east to west slowly for half of the participants and appliances were set to be less efficient for the other half. They were not aware of this beforehand.

They undertook the 22 trials in two sessions (these sessions did not run consecutively on the same day, though no more than 4 days were allowed between sessions) of an hour-and-a-half for the first and an hour for the second, approximately. In the first session they undertook 10 experimental trials and 12 in the second one. Each experimental trial lasted 4 min 20 s. During the first 30 min of the first session the experimenter explained the task and ran three practice trials to familiarize participants with the commands and the characteristics of the task.

Trials 1 to 16 started with the same stimulus configuration. The wind was blowing east with the same intensity during all the trials and appliances were of relative efficiency. For half of the participants, trials 17 to 22 started out with winds blowing east but slowly rotating counterclockwise and ending blowing westward. For the other half of the participants the wind kept blowing eastward, but the efficiency of trucks and helicopters was modified so that they were less able to extinguish the fires.

To ensure that any reader may be able to replicate the experiment, the parameter files are available upon request.

3. Results

The protocols for all the actions were registered for each trial and for each participant. Those protocols were transformed into matrices of transitions between actions. The protocols obtained after running the simulated strategies were also transformed into matrices of transitions.

A stepwise regression analysis was performed for each trial and each participant using the obtained transitions matrix as the dependent variable and the transitions matrices created for the simulated strategies as predictors. The betas in the analyses represented partial correlations between the theoretical, simulated strategies and the participants' actions. For example, if one participant adopted the MOVE-DROP strategy only, a significant beta should be found for the matrix representing that strategy and a nonsignificant beta for the matrix representing the CONTROL strategy.

The results of these regression analyses were used to create a rectangular matrix in which rows represented the participants and the columns represented strategies and trials. There were 44 columns, two strategies for each of the 22 trials.

In order to group participants in accordance with their strategies, a cluster analysis was conducted with the data of significant correlation between their strategies and the theoretical ones in each trial, coded as zeros and ones. A k-means cluster analysis that produced the best discriminative results generated three groups. These groups were of unequal sample sizes: 59 participants belonged to Group 1, 13 belonged to Group 2 and 12 belonged to Group 3. The grouping can be interpreted as follows:

Group 1: Participants whose strategies rarely correlates with CONTROL. They mainly adopt a strategy similar to MOVE-DROP theoretical strategy.
Group 2: Participants who use mainly MOVE-DROP, but not as much as Group 1. They seemed not to use the CONTROL strategy either.
Group 3: These participants adhere to the CONTROL strategy, though they also use the MOVE-DROP strategy occasionally.

To support this interpretation with statistical arguments, an analysis of variance was performed with two independent variables: the groups as a between-subjects variable, and the strategies as a within-subject variable. The dependent variable was the number of times that each strategy was a significant predictor of participant's actions.

The results of this analysis (see figure 3) showed significant effects of both Groups, $F\ (2,81) = 6.24$, $Mse = 12.06$, $p < 0.01$, and Strategies, $F(1,81) = 70.\ 93$, $Mse = 8.11$, $p < 0.01$. The interaction between both variables was also significant, $F(2,81) = 92.31$, $Mse = 8.11$, $p < 0.01$.

These results confirmed the conclusions drawn from the cluster analysis. Groups 1 and 3 had a well defined strategy. Group 1 used a MOVE-DROP strategy and Group 3 a CONTROL strategy. Group 2 had a less defined strategy in which move and drop commands predominate, but not to such an extent as in Group 1.

Once participants were grouped, these groups were used to perform an ANOVA using the overall performance scores as the dependent variable. The overall performance is defined as the sum of all cells that remain unscathed subtracting the value of all burnt trucks. It was expressed as a percentage of the total area. The independent variables were type of strategies (between groups, three levels), type of change (between-groups) and trials 11 – 22 (within-subject, 12 levels). Results showed a significant effect of type of change, $F(1,\ 77) = 4.51$, $Mse = 2251$ and trials 11 – 22, $F(11,\ 847) = 4.38$, $Mse = 126$. The three-way interaction was close to significant, $F(22,847) = 1.36$, $Mse = 126$, $p = 0.12$.

Figure 4 shows that, although groups started at different levels of performance in Trial 11 at the beginning of the second session, they all increased performance

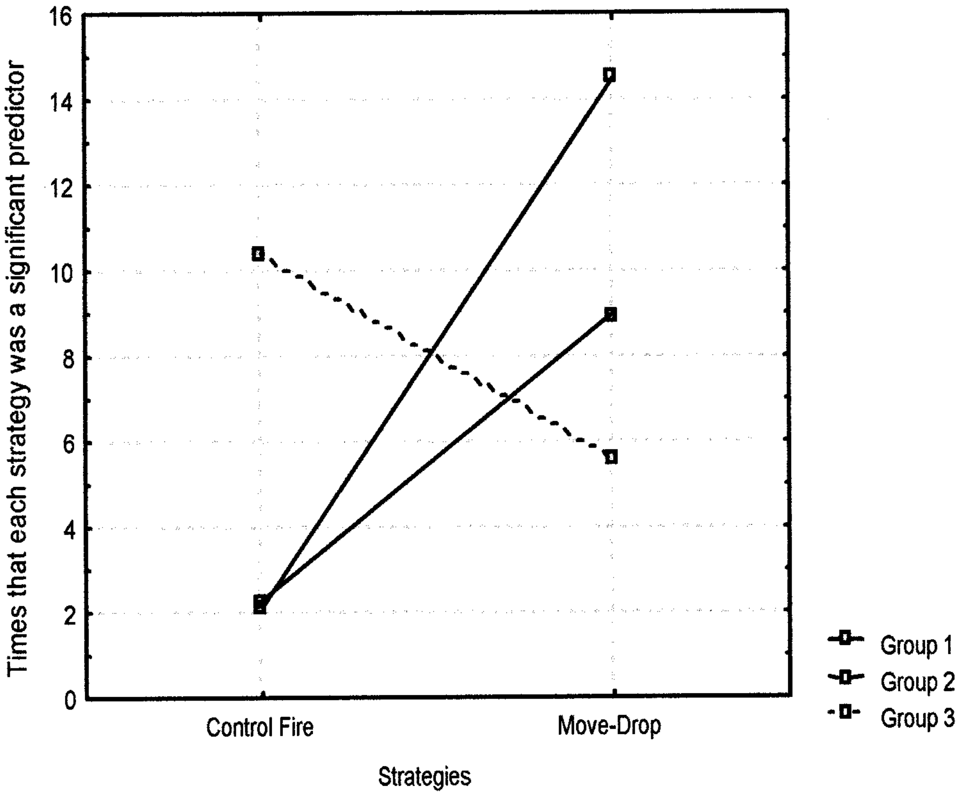

Figure 3. Number of times correlation between theoretical and empirical strategies becomes significant (Trials 1 – 16).

showing a similar learning rate. Group 2 showed the worst performance probably due to the fact that participants in this group had a less well defined strategy.

However, the most interesting results from this analysis are related to what happened in Trial 17 when the environmental changes were introduced. The following conclusions may be drawn from these results:

(1) Participants in Group 1 who were using the MOVE-DROP strategy were affected by the change in appliance efficiency, but not by the change in wind direction.
(2) Participants in Group 3 who were using the CONTROL strategy were affected by the change in wind direction, but not by the change in appliance efficiency.
(3) Participants in Group 2 were not affected by any change. It seems that these participants, who performed worst, had no well defined strategy and kept on learning without being affected by the changes.

4. Discussion

The results from the experiment confirmed the hypotheses. After some time performing a task, a person acquired knowledge about the environmental constraints and developed problem-solving strategies appropriate to those con-

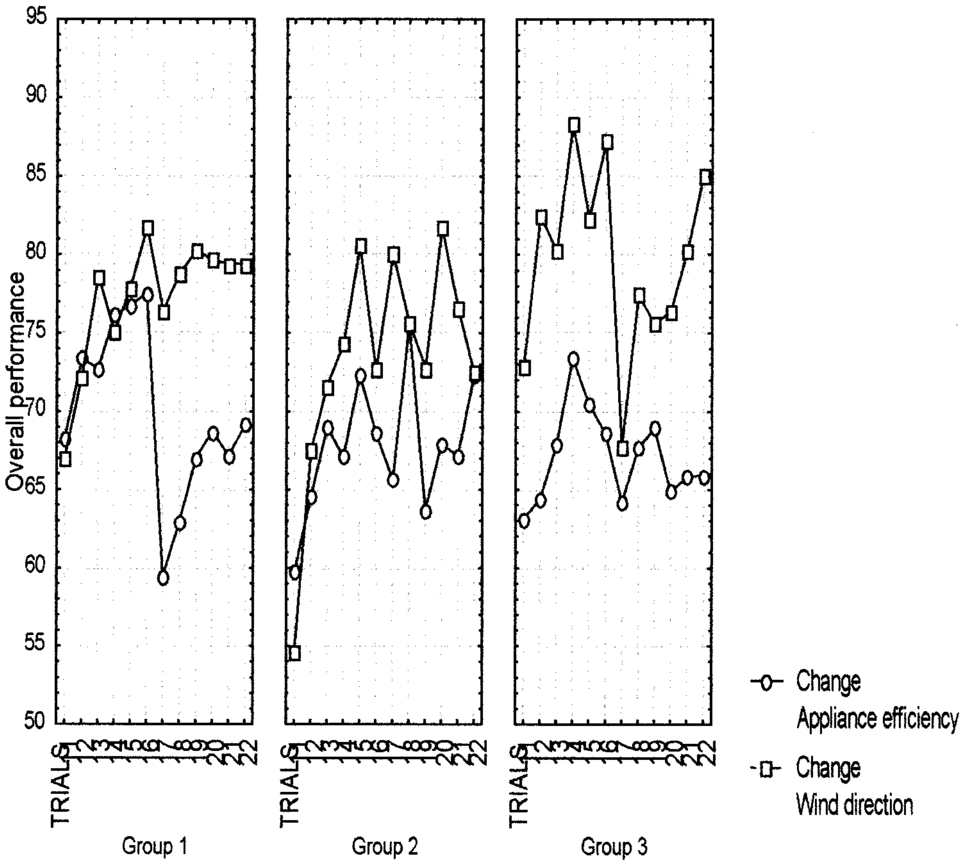

Figure 4. Overall performance.

straints. When the environment changed, people were affected by that change and showed a decrease in performance. However, this observed effect depended on the problem-solving strategy that the person adopted and the particular change in constraints that was introduced. Those participants who used the CONTROL strategy were affected by the change in the wind direction, but not by the change in appliance efficiency. Conversely, participants who used the MOVE-DROP strategy were affected by the change in the appliance efficiency, but not by the wind direction.

The MOVE-DROP strategy consists simply of moving appliances to the closest fire and dropping water there. It does not require making predictions as to where a new fire will start. Therefore, the direction of the wind had little effect on their overall performance. However, a person using the CONTROL strategy needed to predict the direction in which the wind would be blowing and create a control fire according to that prediction. The fire will spread depending on the wind direction, and as a result, the person selects the location for a control fire depending on that prediction.

The main implication of these results is that they appear to explain the apparently contradictory predictions derived from cognitive ergonomics and cognitive psychology theories concerning the effect of environmental changes on expert performance. Experts are affected by environmental changes, but only when these changes are related to the particular strategies that each expert develops.

These results could lead to further research towards developing a theoretical model of the possible cognitive strategies of complex problem-solving in dynamic tasks and a theoretical model of these dynamic tasks. As has been proposed by Vicente and Wang (1998), the two theoretical models should be developed in parallel because it would be impossible to explain problem-solving behaviour with only one.

The second, and equally important implication that can be drawn has a broader theoretical and methodological relevance. The literature review on this issue points to a situation in which two contradictory theoretical predictions could be made. On one hand, there are theories that predict that any environmental change will affect people's performance. On the other hand, there are theories that predict that people adjust rapidly to environmental changes and that their performance is not affected significantly by these changes.

With these contradictory predictions, we could have: (1) designed an experiment in which we train participants in a problem-solving task; (2) introduced a change, with no reference to any theory of the environment; (3) averaged the performance of participants in each group; (4) evaluated the effect of the change on performance. Then, we could imagine four possible outcomes (O) from the hypothetical experiment proposed:

- (O1) We could have changed the wind direction and all participants might have used the CONTROL strategy.
- (O2) We could have changed the appliance efficiency and all participants might have used the CONTROL strategy.
- (O3) We could have changed the wind direction and all participants might have used the MOVE-DROP strategy.
- (O4) We could have changed the appliance efficiency and all participants might have used the MOVE-DROP strategy.

Outcomes O1 and O4 would lead us to conclude that environmental changes affect participant performance. On the contrary, outcomes O2 and O3 would lead us to the opposite conclusion, that is, that environmental changes do not affect performance. However, as is obvious from our results, both conclusions would have been wrong.

However, our research strategy, more in line with product theories such as CAH (Vicente and Wang 1998), consisted of: (1) designing the experiment to train participants in a problem-solving task; (2) differentiating participants according to their possible strategies; (3) selecting the changes to be introduced based on their relationship to those strategies; (4) evaluating the effect of those changes on participants' performance separately as a function of their strategies.

This research strategy was successful in showing that human error research should find explanations of the human errors in the interaction of cognitive processes and environmental conditions. With this in mind, the further exploration of this hypothesis in the context of a general model of decision making in complex problem-solving tasks is planned.

Another important contribution of this research is the methodology used for the evaluation of problem-solving strategies. Although transitions between actions have already been used to analyse problem-solving strategies (i.e. Howie and Vicente 1998), the methodologies that used them have done so mostly in a qualitative way.

Christoffersen *et al*. (1997), for example, analysed performance errors in a 6-month-long experiment using the control task microworld Duress, but their analyses are mainly qualitative. The present method is one step toward designing quantitative methods for identifying problem-solving strategies in this area.

Finally, it is worth discussing the definition of expertise used here. In most research, an expert is defined explicitly or implicitly as someone who has spent 10 years of extended, deliberate practice (Ericsson and Smith 1991, Ericsson and Lehmann 1996) in one particular area. However, the experts used in other research, related to laboratory studies on process control like the present one (see Vicente 1992, used also in Vicente and Wang 1998), were engineering graduate students whose only direct experience of the complex system was restricted to an hour-long general introduction given to all participants before the start of the experiment.

The reasons for using 'laboratory-created' expert performers instead of real experts vary but these are some of the reasons:

(1) Many of the studies normally cited in expertise research do not measure domain expertise, but simply infer it from the length of experience in the domain. Nevertheless, it has been demonstrated that the length of professional experience is a weak predictor of performance in representative professional activities (for a list of these activities, and corresponding research, see Ericsson *et al*. 2000).

(2) Experts are a sparse resource and their time is so valuable that it becomes difficult to assemble a representative number of them in a laboratory in order to run an experimentally-minded program. When controlled conditions have to be used, the materials usually become relatively abstract or unnatural to them. For example, chess masters do not recall normally chess board configurations in real life; they just play chess. This phenomenon has been raised as one of the central dichotomous distinctions in Vicente and Wang's expertise theory (Vicente and Wang 1998): 'contrived' vs. 'intrinsic' tasks. They argued that when these 'contrived' tasks are used and do not maintain the real task's constraints, the expertise advantage will disappear. In fact, correlations between 'contrived' test and real expert performance are quite low (i.e., De Groot and Gobet 1996: 60).

(3) Some interesting real life situations ('Natural materials', in Vicente and Wang's terms) are hard to reproduce in laboratory conditions, at least in what one would normally understand by laboratory conditions. For example, it would be difficult to reproduce the natural environment of an expert in some sport. However, this domain, as well as some others where the external environment is rapidly and continuously changing (like air traffic control, piloting, or performing a surgical operation) are very interesting due to the high implications of human error that can be committed in these situations.

Thus, this research was based on microworld tasks since they appear as an appealing alternative to the 'real world' expert research. Instead of using a real life expert, the experimenter generates a scaled, controlled situation where the distinctive features and complexity of the original setting are maintained, but designed in a way that can be mastered in a few experimental sessions. At the same time, the amount of practice needed to reach an asymptote in this kind of task is shorter than one would expect (see the automation literature, for example Logan, 1988). It is felt that this was the correct choice and that the results have also shown the validity of microworld environments for conducting complex problem-solving research.

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