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A methodology for analyzing the dynamic collective organization of nuclear power plant operators in simulated accidental situations

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This research deals with modelling of emergency operation of a nuclear power plant involving hard-copy instructions distributed among different operators. Emergency operation is seen here as *experienced, embodied, dynamically situated (including socially), indissolubly individual and collective, and cultural.* Based on preliminary modelling of significant elementary units (SEU), sequences and macrosequences of the courses of experience of various agents, and on the collective interaction of those SEUs and sequences, two sorts of progress were made : the first, which lies just slightly lower than the SEU, concerns modelling of the *dynamics of attention windows*; the second concerns the *dynamics of openings*, i.e. the diachronic and synchronic relationships between the courses of experience of the different agents.

Keywords : Situated action, Modelling individual & collective action, Emergency operation, Computer Supported Cooperative Work.

Introduction

This ongoing research is part of a long-term dialectic between ergonomics research and ergonomics practice undertaken some time ago by the two teams (see, for example, [2] and [3], and [11]). It looks at emergency operation of a nuclear power plant in which hard-copy instructions are shared out among the reactor and water-steam operators, the supervisor, the operations manager, and the safety engineer, and is based on full-scale simulator tests. The five agents—who may be joined by auxiliary operators—work in a space divided into functional zones, written instructions in hand. Audio-video recordings of all control-room activity and of very short self-confrontations of the reactor operator and supervisor were systematically analysed for two 150-minute tests chosen for their common complexity and their differences. The objective of the research is to make progress in modelling of this activity.

1. Theoretical and methodological framework

The theoretical and methodological framework of this research is that of *cognition seen as experienced embodied, dynamically situated (including socially), indissolubly individual and collective, and cultural* :
* *experienced cognition* : this is what some authors call "the explanatory gap of cognitive sciences", i.e. absence from the mainstream—so far—of a description and explanation of actors' access to emotional, sensory, and cognitive processes, which obviously does not imply that such access is total or even correct;
* *embodied cognition* : cognition, decision, action, communication, but also emotion, attention, etc.—taking these terms in their common meanings—are inseparable;
* *dynamically situated cognition (including socially)* : cognitive phenomena are not situated merely in the head, or even merely in the body, but also in the relationship between corporal dynamics and situational dynamics;
* *indissolubly individual & collective cognition* : individual cognition includes a relationship with other agents, including through the traces they leave in the situation, and collective cognition cannot be described and explained without considering its relationship with individual cognition;
* *cultural cognition* : this culture is more or less shared by the agents.

This theoretical and methodological framework can be seen as a development of what was implied in the notion of situated action. It may be remembered that the theme of situated action was brought into the public domain in 1987, with the book by Lucy Suchman [5]. Since then a variety of authors (see [13] in particular) have reduced it to i) a methodological innovation, the study of cognition in the field, and ii) a theoretical criticism of the notion of plan and of the reduction of man-machine interaction to carrying out procedures or instructions. Now, if indeed there is any methodological innovation, it is very relative, since methodologies for studying cognition in the field were developed a long time ago, particularly in the work analysis developed by the French-language ergonomics movement. And if indeed there is any theoretical criticism, it is far from being the essence of the theoretical proposals made. For as an alternative to cognitivism, i.e. to the paradigm of "man as an information-processing system" as formulated in [4] for example, Suchman proposes considering "lively, moment-by-moment assessment of the significance of particular circumstances" and "to explore the relation of knowledge and action to the particular circumstances in which knowing and action invariably occur" ([5], p. 178). This involves not just describing situated action, but also proposing situated action/cognition as a strong theoretical hypothesis. This strong hypothesis has critical and constructive aspects. The well-known theoretical critical aspect is that human actions are far from being generated and controlled from start to finish by plans, or in other words, by internal representations specifying in full the different steps in the performance of human actions, whether these internal representations are produced directly by the agents or are the result of their reading procedures or instructions. The theoretical constructive

aspect is that plans and procedures or instructions are just some of the resources available for carrying out actions. The fundamental point to be considered is not so much the problem of the plan or of the procedure or instruction as the idea that action/cognition calls on other resources, i.e. the material, social, and cultural characteristics of the environment in which events occur and which constitute the situation of the agent(s). As these characteristics can change at any time, to adapt to them individuals adjust their actions to the new environmental circumstances. This adjustment is done on an improvised *ad hoc* basis. Seeing situated action/cognition as a "strong hypothesis" thus implies that cognition is "situated", including in laboratory experiments, and that here too, research procedures taking account of this situated nature must be developed.
While one of the major contributions of the situated action/cognition movement is that it highlighted the opportunistic and improvised nature of human action and co-operation, together with its material and socio-cultural anchoring, this contribution has been limited to a scientific practice with sparse interest in systematic modelling of the phenomena studied, and it has thematized essentially material anchoring of cognition, to the detriment of corporeal and cultural anchoring. In addition, while calling on the accounts of the agents concerned, it has not thematized the fact that the agents too experienced personally these accounts and the corresponding actions carried out. To go beyond these limits and, in so doing, raise things to the level of scientific requirement formulated and practised by Herbert Simon in connection with an entirely different paradigm (refer in particular to the introduction to [4]), it is necessary to develop a "harder" phenomenology, i.e. one directed towards a systematic modelling of the greatest possible wealth of empirical data. This amounts to : defining an adequate paradigm for human cognition (versus the paradigm of "man as an information-processing system") and the corresponding theoretical object(s); defining an observatory for these theoretical objects at the level of the "minimum theory" of data collecting on human cognition, as specified by Ericcson & Simon in "Protocol analysis" [1]; defining a phenomenology or analytical model of situated action/cognition, i.e. a theoretically coherent set of descriptive categories of human experience, of experienced cognition, or, in other words, a generic analytical model of it (as compared to the descriptive categories of "problem-solving graphs", those of "information status" and of "information-processing operators"); defining a generic synthetic model of situated action/cognition (as compared to today's conventional "cognitive modelling" complying with the paradigm of "man as an information-processing system"); defining a method for designing practical models, i.e. models intended to guide the designers of technical spaces and tools in the control room, of instructions and their supports, and of the training and organisation of agents.

2. Principles of the modelling carried out

This research takes as granted the paradigm of living systems defined by Maturana & Varela (see [12], for example), along with the theoretical objects and observatories defined by [7], [9], and [14], and is restricted firstly to construction of an empirical analytical model dealing with the activity of agents as they experience it at any time, and more precisely with what we call here *collective interaction of courses of experience*. The research makes it possible to extend, enrich, and more effectively validate the analytical and synthetical comments that can be made : empirical comments on the production of agents' experience at any time, based on the characteristics of their status (corporeal anchoring), their situation (material and social anchoring), and their culture (cultural anchoring), pending analytical and synthetic modelling of that production; ergonomics comments on the possible consequences in terms of the design of instructions, interfaces, and organisation.

The research picks up from work done previously by the EDF team (see [2] and [3], and, more remotely, [9] and [10]) : construction of recording, observation, and verbalization data from emergency-operation tests (verbalization = self-confrontation of the main operators); transcription of each test (lasting between 120 and 150 minutes); special transcription of data concerning the reactor operator and the supervisor (which gives rise to different theoretically-based decisions, in particular with respect to the description of the actions performed); reconstitution of the tracking of instructions based on pages of the hard-copy emergency-operation instructions used; salient events noticed by observers; preliminary analytical modelling in terms of significant elementary units (SUE), sequences, and macrosequences of each agent, and in terms of the collective interaction of those significant elementary units, sequences, and macrosequences; preliminary series of empirical and ergonomics comments arising out of the preliminary modelling.

The essential principle of the preliminary analytical modelling and its extension under the present research project is to determine—retrospectively—, from a given moment in the activity of agents, which periods of that activity are perceived as a unit by the agents, and what sort of relationships the agents establish between those periods. The units and relationships set up at a given moment may last throughout the rest of the activity, or they may be called into question. The relationships between units build units of a higher order than the previous ones. These higher-order units can be continuous or discontinuous.

Some of these units and relationships can be elicited by the agents themselves, through their interviews and self-confrontation. Others can be inferred by analysts, by comparing with other parts of the test transcripts (which include continuous observation and recording of the behaviour of agents and various forms of verbalization by those agents, particularly self-confrontation), but also—subject to some precautions—by means of the experience of analysts and their knowledge of the training the agents are given, the tasks they perform, and the tools they use. This modelling produces a graph of the concatenation, imbrication, and partial overlapping and embedding of units. The units are themselves categorised in terms of significant structures, by considering the different sorts of relationships between the significant lower-order units. The significant structures that the previous studies determined by comparing a theoretical approach and an inductive approach are different kinds of elementary structures, diachronic structures (sequences of different orders, series of different orders), and synchronic structures, i.e. structures that are indifferent to temporal succession (synchronous structures of different orders), the definition of which can be found in [9].

The starting point for modelling the collective interaction of the courses of experience of certain agents with an essential role in a given collective situation is the models for each of the agents concerned, i.e. the graphs of concatenation, imbrication, partial overlapping and embedding of significant units of their activity. The modelling results in several parallel graphs and allows the relationships between the units of which the graphs are made to be determined.

The heuristic value of this modelling of courses of experience and of their collective interaction lies in : its utility in terms of the intelligibility of the activity of the agents in the units and relationships determined; the possibility it offers for close comparison between different transcripts and fragments of transcripts; the possibility if offers for inductive construction and specification of generic categories with respect to the activity of agents; the effective constraints in the activity of agents that can be detected from it, together with the categories of constraints that can be defined, these constraints concerning the current state of agents, their material situation (particularly the content and presentation of instructions, the type and layout of indicators in the control room, etc.), organisational situation (the roles of different agents, their possibilities for communication, etc.), and cultural situation (commonness and differences in training, experience, etc.).

The first modelling of SEUs, sequences and macrosequences, and their collective interaction makes it possible to specify : (1) the string and embedding of dynamic contexts of situated interpretation of instructions by the supervisor and reactor operator, and their constraints and relationships with the demands of the process; (2) the co-operation between the supervisor and the reactor operator and between them and the other agents, its constraints and effects; (3) information concerning the competencies of the supervisor and reactor operator, and the effective, in-situation mobilisation of those competencies, together with the constraints, effects, and compatibility with the process of that effective mobilisation.

To extend this first modelling, the SEUs determined from the following criteria are taken as granted : continuum of perception-action of situated interpretation/following of instructions; period of stoppage on an instruction or set of instructions; continuum of communication with other agents regarding a given topic; periods with varied contents in which the agent departs from the instructions. On the other hand, we consider the resulting sequences and macrosequences as being simply a first step in the revelation of more complex structures, both diachronic and synchronic.

This research thus makes it possible to make two kinds of modelling progress : one—just slightly below the level of the SEU—concerns modelling of the *dynamics of attention windows*; the second concerns the *dynamics of openings*, revealing the diachronic and synchronic relationships between SEUs, sequences, and macrosequences of the courses of experience of different agents. This progress in modelling is developed iteratively, as was done in the case of the previous modelling : determination of the different kinds of links each SEU has with others, i.e. the openings of different types; determination of attention windows and their role in the local development of courses of experience;

analysis of the series of different types constituted by the links between SEUs; analysis of the different kinds of synchronic links between these series, as seen from the point of view of each agent; formulation of the empirical and technological gains obtained by means of this modelling. Such a process of modelling is not monotonic : at each step, one has to look back to the previous steps to detail and refine their results, or even to call how they were done into question (which, with respect to the construction of data, can obviously only have an effect on the next study or stage of research).

3. Score reading, disturbance, and dynamics of attention windows

Let us look first at the dynamics of attention windows. Whenever information is acquired by reading signs (as opposed to simply identifying presence/absence or threshold overruns, which are a matter of indices or signals), attention has to be focused. In other words, there is a moment when the agent can pay attention to a single thing, when he momentarily excludes other information from his field of conscience, when he sets his mind to taking in the meaning of the information read, something he can do only if he does only that. It is therefore reasonable to assume that there is a strong relationship between reading activity (reading of hard-copy, but also reading of screen displays or plots) and a temporary mind-set in which the field of attention is focused on a single thing, temporarily inhibiting and excluding everything else. Now it is precisely this sort of reading activity which dominates emergency-operation activity driven by procedures. In general terms (with substantial variations depending on their role), agents read text, move to a different location in the control room, adjust controls, communicate, and wait. But first of all, they read and read : main procedures, auxiliary procedures, etc. This reading can in fact be called “score reading” : each item or set of information read (an individual instruction, a test, etc.) on hard copy corresponds to an action to be carried out (go get information to document an instruction) or a test to be done (change documents and open another, communicate information, phone another agent, carry out a control action, make an adjustment, etc.). The notion of “score” is that of sheet music, where each sign is meant to produce a determined action : play a certain note, for a certain time, with certain alterations, with a certain expression, etc. Taking the analogy a little further, a music score is the transcription of the result to be achieved, the notation of the sound expected. However, this notation is but a poor reflection of what the player has to do to get that result, for in order to play the notes correctly, he has to interpret the written music, correct it, and complement it to make it an effectively adapted guide for action. A beginner is incapable of knowing exactly how to play the music on the paper in front of him once it starts getting complex, which hand plays what, for example (on piano). Similarly, if operation instructions are the end result of a whole process of capitalization of knowledge and experience, agents have to add a good dose of knowledge of their “scores” in order to apply them correctly. It is a matter of expertise, constitution of a procedure-reading habitus which appears to be broadly underestimated, yet which is foremost among the preoccupations of simulator-training supervisors who see it as a central requirement.

What must be stressed is that there are constant changes in focus/mind-set. A line is read, an instruction is taken in. To do this, the agent has to discern precisely what he perceives, so he restricts his field of visual perception. In most cases this reading leads both semantically and spatially to another instruction, but also to movement of the agent to another point in the control room, and to another kind of reading—as occurs when the agent reads a value off a display—, or it can take him to another document which must be extracted from its classification system and thumbed through until the right sheet is found. There is then a new focus of attention, etc., one characteristic of which is that sooner or later the agent will go back to the main document that he set down previously, and pick up again precisely where he left off, so as to ensure the imperative of continuity of his sequential reading. To these changes in focus which must be managed by the agents' working memory are added interruptions which can cause them to lose the thread they are following. These interruptions can be diversions of occupation (and therefore of focus) : while the agent is proceeding with an adjustment, something extrinsic to that activity interrupts him and requires him to suspend his current occupation and turn to something else. More locally, these interruptions can be changes in focus : while the agent is reading off a series of values on a screen, the phone rings, or another agent needs an answer to a question; the agent responds quickly to the solicitation and immediately returns to his instructions. For example, just as the reactor operator starts implementing the Orientation and Stabilization Document (OSD), the operations manager interrupts to ask if he has called the safety engineer. "No. Do it, will you, Colin", says the reactor operator. The reactor operator has been momentarily interrupted, but it is clear that he does not need to reflect on the matter or take in new information to be able to answer the question, but nevertheless he does more than just answer since he delegates performance of the task to the person who asked the question. Which implies that he gets an answer back since his own answer contains a question. There is indeed an interruption, but all the conditions point to there being no change in occupation, merely a momentary 'blip' authorised by the fact that the question is oral and consistent with the reading in progress, and because the activity required to answer does not require a new occupation that would compete with that already engaged. In addition, it can be assumed that the OSD is sufficiently fragmentary for it to accommodate simple interruptions. Equally, it can easily be imagined that in certain activities requiring closer attention, the simple fact of being addressed in this manner could more or less seriously affect one's state of concentration and compromise the efficacy of the activity in progress.

These interruptions, and particularly interruptions to occupations, are potentially sources of errors when agents return to pick up an activity where they left off. For instance, a phone rings during a basic-cycle phase, just when the reactor operator is documenting a test from the readout on a screen. The agent decides to interrupt this phase of work in progress, i.e. without completing it and mentally "bookmarking" his instructions. When he comes back to it, he picks up at the phase of work interrupted, but at the wrong place in the procedure sheet. Interruptions such as this require agents to perform additional marking and verification tasks in order to ensure the continuity of their activity. For example, during the same phase, the supervisor asks for information while the reactor operator is reading off values from plotters. The operator does not reply immediately; first, he finishes his readings, then goes back to his procedure, and finds that he has to go to a new page; he turns to that page and only then turns to the supervisor to answer. He did not take the risk of interrupting the continuity of application of the instructions before reaching a stable and easily identifiable point. Conversely, agents whose activity requires them to interrupt the activity of other agents develop an additional activity of following the other agents' activity and controlling the interruptions they have to provoke. For example, the reactor operator tells the supervisor the conclusions reached from implementation of the OSD, as he is required to do by instructions. He gets the ECP1 (Reactor Control Status 1) instructions ready and, without opening them, says to the supervisor "OK, you can run your loop". In the ensuing period, he sits back, holding the instructions closed under his arm, says nothing, and makes no verbal or non-verbal communication other than a general sign of withdrawal. When the supervisor has reached his own conclusions—the same as the operator's: follow the ECT1 procedure (the one corresponding for him to ECP1)—he confirms "Yeah", and, in a different register, "Here we go" to signal that he is starting to implement the instructions. These two sorts of additional activity dovetail together.

4. Control with distributed instructions and synchronic management of openings

Another property of the course of action of each agent is its opening to a more or less indeterminate future. This is why we detail the common-sense notion of occupation by introducing that of *open action*, or, put more simply, *opening*. An elementary action can be fully completed : thus, looking at the simplest example, the agent makes phone call, gets hold of the right person, and gives his message : "You're wanted in the control room". In this case, once he has hung up, the operation has been carried out and completed. On the contrary, if the agent makes a call and cannot speak the right person, he leaves a message asking to be called back. In this case, when he hangs up, he creates an opening or, in other words, an action which has not been completed, which remains open to a future end. The same can apply in the first case too if there are other contingencies accompanying that of arrival of the person called, such as briefing him on the situation.
In fact, this notion of opening is a very general one. Its relevance extends well beyond cases like this. As soon as a test begins, an opening is created for each operator and experienced by him : operation under normal circumstances that will be turned into emergency operation, in one way or another. As soon as any operator gets involved in an emergency procedure, an opening is created : the situated following/situated interpretation of the instructions, until it has been successfully accomplished or until the evolution of the process means he changes procedure. The notion of opening even brings us to a set of even more general

hypotheses on human activity, synthesised by the notion of *hexadic sign* (see [8]), which cannot be detailed here.

Openings (occupations) and attention focus should be considered jointly. Let us look at an opening. The moment at which an opening is created, progresses, or closes may fit into the sequence of action managed coherently by the agent; it may also occur out of the blue at any moment, while an attention focus is going on. Consequently—to take up the previous example again—the moment the person calls back, having been given the message, may be precisely when the operator is recording information to document the response to an instruction, causing him to interrupt his reading to answer the phone. There is a break in the focus of attention, and once the opening has been closed (or has progressed)—i.e. the phone has been answered—, the agent has to pick up again exactly where he left off, or just afterwards, having often moved several metres from the panel to the telephone. The structure of an opening therefore leads towards potentially inopportune closure—or progression—; in all cases, whatever happens, or when it happens, is beyond the immediate control of the agent who initiated the opening. The graph of the reactor operator's and supervisor's openings during a test allows for analysis of the interruptions in focus of attention and of their diachronic and synchronic management of openings. It also serves as a base map for closer local analysis of the dynamics of attention windows generally.

The openings in the activity of an agent at any time build up. The time between creation and closure of an opening can engender a more or less nagging sense of worry for the agent who continues to manage the rest of what the instructions require him to do. The number of openings in place simultaneously and the agent's skill at managing them synchronically are part of conditions which can diminish vigilance, induce moments of confusion, and lead to distraction. None of these conditions alone can do this, but together they may. For example, in the reactor operator's and supervisor's analysis graph of openings for one of the tests systematically analysed, about an hour after the start the reactor operator is simultaneously managing situated following/interpretation of the ECP2 instruction, in the knowledge that the emergency continuum will eventually require the next set of instructions up, ECP3 (following a previous message from the supervisor), while carrying out the instructions of an auxiliary instruction sheet (RFLE58), and at the same time the supervisor is simultaneously managing situated following/interpretation of the corresponding ECT2 instruction, in the knowledge that the emergency continuum will eventually require the next set of instructions up, ECT3 (following a previous message from the operations manager), is looking through the instructions regarding the criteria for changing to ECT3, is examining and carrying out actions concerning the state of a particular system (ASG Auxiliary Feedwater), and is also awaiting the results of an *in situ* inspection of the system by an auxiliary operator.

While modelling of the changes in focus of attention and opening, filling, and closure of openings concerns the course of action of individual agents, i.e. that part of their individual-social action which is significant for them, it in fact points towards the collective activity of the entire control team, for these events are the result not only of the specific activity of each agent, but also of the relationships each agent has with activities of other agents. Each agent is supposed to follow his instructions (ECP for the reactor operator, ECT for the supervisor) without giving a thought to the others, except at special predetermined times when either he has to give some of the others information about the system controlled or the point he is at in his instructions, or he and the others have to change instructions. We saw an example of the latter case above, concerning the change from OSD to ECP1. It can be seen that in fact the agents interact with each other well beyond these particular moments. They observe each other, organise their access to resources (operations sheets and logs, for example) and their respective instructions to auxiliary agents, express their feelings, co-ordinate with each other, wait for each other *extra*-instructions, exchange information and diagnoses/prognoses on the dynamics of the system, criticise each other's actions and movement through the instructions, and sometimes even put their minds together to collectively solve problems. Most of these events are not "meta-functional", i.e. they do not concern just the construction and maintenance of the particular social relationship of emergency operation, but comply with the constraints of operation with distributed instructions. For example, through the instructions he follows, the supervisor checks the operations carried out by the reactor and water-steam operators. If he is ahead of them, nothing prevents him reading even further ahead, but he will have to go back over the instructions to actually carry out the checks. If he is too far behind them, his verification will be too late. So to the above description of the simultaneous openings of the reactor operator and supervisor respectively one hour after the start of the test must be added openings concerning what each of them thinks of the work of the other : one of the reactor operator's opening is to not disturb the supervisor during his laborious search for the criteria for changing to ECT3, and to get through ECP2 as quickly as possible and find a way to ECP3 that would overcome the problem; one of the supervisor's opening is to wait for the reactor operator to change to ECP3. Parallel modelling of the activities of the reactor operator and supervisor and of the interactions between them thus gives a vision of the collective activity as it is co-constructed by the two agents and their particular dynamic situations, including other agents. The procedures—including auxiliary procedures—sheets, logs, and the entire control room are tools for capitalising on and managing the knowledge which contributes more or less successfully to this co-construction.

Conclusion

This progress in analytical modelling helps detail and create a better foundation for the empirical and ergonomics comments made previously, and also engenders new empirical and ergonomics comments. Some of these comments arise directly out of the model. Others arise indirectly, and are the starting points for subsequent development of the model. In particular : (1) this research reveals the *real requirements for competence* of agents, something that goes well beyond simply following written instructions, particularly those requirements concerning *extra*-instruction communication with other agents, including those concerning

adjustment of the timing of actions by different agents and those concerning the precautions to be taken with respect to disturbing other agents and how to deal with being disturbed by them; (2) it allows for analysis of *the genesis of errors and their contributing factors*, in the written style of the instructions and in variations in that style, in the quality and multiplicity of simultaneous openings, in interruptions in focus, and not just in "human weaknesses"; (3) it introduces questions about *the roles allocated to the different agents*, and in particular to the supervisor who must, on one hand, follow instructions for checking the actions of the reactor and water-steam operators, and, on the other, in dealing with the operations manager, step back from the instructions and consider the evolution of the process, and who must also carry out certain operations detailed in auxiliary procedures that the two operators are not able to carry out within a reasonable time. A further appreciable aspect of the modelling carried out is the analysis graph which enriches the available *resources for dialogue with designers*.
In sum, research such as this reveals the interest of a long-term dialectic between ergonomic research and ergonomics practice : the former makes for development of the latter, and the latter provides a starting analysis and questions for the former, the two being performed at once by official researchers and official practitioners.

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