Depth of processing and design-assessment of ecological interfaces: Task analysis

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Despite the cognitive vocation of a number of studies on the comparison of interfaces in sensitive industrial sectors such as the nuclear sector, and in spite of the presentation of new frameworks for both task analysis and reducing the mental load, one vital question remains: how does psychology enter into these studies? Very often the principle of depth of processing is the basis for interface design-assessment approaches in operating situations like those of nuclear reactors. This then justifies the use of a methodology based on recall. After presenting how this principle, which stems from the memory field, is the basis for the different interface designs recently proposed in the literature and the validation approach associated to these technical propositions, we present a pressurized water reactor operating situation that demonstrates the same willingness to act on reasoning through information displays. For powering up conditions, we show how integration of different representational levels has been achieved, and provide evidence for a Physical vs. a Physical and Functional display. All these features indirectly show that recent proposals on ecological interface design have some validity for real work situations, provided a context is selected. Finally, from this analysis, we define, by considering success as the limits of past experience, the conditions under which a recall technique can be used to demonstrate the efficiency of these new tools.

1. Introduction

In the field of interface design and assessment, recent studies have emphasized two ideas: that of “externalizing mental models through the display” and that of using the recall paradigm. A hierarchy has been proposed for treating the significant characteristics, and different forms of information display have been compared using a memory task (Vicente, 1992a; Moray, 1993). Recall performance was used to test the relative efficiency of the interface in accordance with the following principle: the better the access to the meaning (in other words the better the interface), the better the memorization. It is true that the principle of depth of processing has been a central idea (a major framework) in the work undertaken on memory since the publication of Craik and Lockhart (1972); the positive association between depth of processing and mnemonic performance having been verified on numerous occasions (Giboin, 1978, 1979; Lockhart & Craik, 1990, for reviews). It is therefore relevant to find out whether a particular form of information display reduces the load; in other words when analysing these works if they provide better processing of the meaning by using recall as part of the diagnosis (Vicente, 1992a; Moray, 1993).
This same relationship has already been employed, even if not identified as such, in the ergonomics studies adopting a memory paradigm as the processing study tool. This is notably the case in studies on operational paradigm and functional representations (complex problem-solving tasks such as air traffic control, and logic error diagnostic tasks in computer programmes). These have highlighted, at different levels, the relationship between the depth of information processing and the quality of mnemonic performance (Spérandio, 1975; Michard, 1978). For example, concerning the relative memorization of different information, certain information is memorized better than others because it is more important to the task in hand (Spérandio, 1975). It is therefore relevant to find out whether a particular form of information display reduces the load; in other words, when analysing these works if they provide better processing of the meaning by using recall as part of the diagnosis (Vicente, 1992a; Moray, 1993).

The principle of depth of processing, as well as memory tasks, can be used to resolve an applied problem: interface design assessment of a pressurized water reactor operating situation. This view was endorsed in our research. Although empirical studies conducted on memory performance in a work situation have outlined results and new memory methods that could be used in research on ecological interfaces at the assessment level (Terrier, 1996; Terrier & Cellier, 1997; Cellier & Bauza, 1997; Terrier, Cellier & Grosjean, 1988), empirical data will be only evoked at the end of this paper. The aim of this paper is to provide evidence for the value of this rationale at the design level when an existing work situation is observed. In the first part of the paper (Section 2), the relevance of the principle of depth of processing in design is shown on a different basis: the use of an abstraction hierarchy in describing the world domain, the integration of different representational levels of description of the process in the display, and more generally the fact that different design proposals pertain to a similar logic. In the second part of the paper (Section 3), the presentation of an existing situation demonstrates that the theoretical and technical proposals reviewed and coordinated by referring to the logic of depth of processing are relevant for complex situations such as a Pressurized Water Reactor (PWR). In the third and last part of the paper (Section 4), success and limits at the level of assessment of these new artifacts are outlined on the basis of important characteristics observed in this work situation.

2. The interface design approach
Two increasingly employed ideas indicate that the design of interfaces is a process aimed at reducing mental load: Direct Manipulation Interface and Direct Perception Display. The construction of these interfaces “aims at reducing the mental load of the end user by optimising communication between the interface and the user” (Beltracchi, 1987, p. 483). Taking the example of video games to explain what a direct manipulation interface is, Beltracchi notes that the commands are physical tasks (pressing buttons, moving the joystick) with the results appearing directly on the screen, hence the term direct. He points out that the term direct perception interface expresses the principles used in the design of industrial interfaces: the interface displays what is happening in the process controlled by the subject. If the design of an efficient interface is guided by the aim of reducing mental load (cf. Woods & Hollnagel, 1987), the relevance of the principle of depth of processing becomes clear due to the significance of the role played, and still
being played, by a similar principle: the abstraction hierarchy used to build and assess these interfaces.

In this first section, the relevance of the principle of depth of processing in design is shown on a different basis. First (Section 2.1), the use of an abstraction hierarchy (AH) in describing the work domain, and the problem inherent to the use of an AH when implementing the hierarchy in the displays: the problem of multiple process models that can be used by the operator appears to be a problem of orienting the processing. Second (Section 2.2), although not every author proposing interface designs refers explicitly to the abstraction hierarchy and ecological interfaces, a number of display techniques have been suggested in order to express factors deemed important to the general functional purpose and the general or abstract functions performed by the controlled process. When we examine how authors present their reasons for proposing several interfaces and display techniques, it can often be seen that the interface uses the abstraction hierarchy and that it concentrates on the higher levels of this hierarchy. Even the usefulness for task analysis of high level of description of the work domain through the display is apparent for some proposals (see Bennett, Toms & Woods, 1993, p. 77). Note that although an eloquent contrast of the similarities and differences between approaches would certainly be a valuable contribution to existing literature, the perspective adopted here is to delineate a similar willingness to act on reasoning within different approaches: to better communicate the meaning (status of the process). Highlighting this similarity is important in order to understand that the use of memory recall performance for testing the proposals is suited, and to show that behind the different labels used by authors, different proposals and techniques can be assumed to rely on the abstraction hierarchy. Still, one might argue that this does not indicate the relevance of previous work on nuclear plant displays for industrial applications because most of this work is either theoretical or laboratory based. This problem will be addressed in the subsequent general section.

2.1. THE ABSTRACTION HIERARCHY

In studies on nuclear reactors, the principle of the abstraction hierarchy (Rasmussen, 1985) has been proposed by several authors as being a relevant framework for task analysis and load reduction. The reasoning is the following. Different representations (and perhaps different mental models) exist that allow the state of the system controlled by the operator to be described in accordance with the level of operating knowledge required: inexperienced operators controlling the system, or experienced operators having to react to an abnormal event requiring this level of control. For example, when an experienced operator encounters an abnormal situation, the state of the system can be assessed using different hierarchically organized models: physical form, physical function, generalized function, abstract function or functional purpose. At the design level, the analogy with the depth of processing rationale—the existence of different levels of abstraction in processing—lies on the fact that there exist several levels of abstraction for describing an information ranging from its detailed components, to a global description level at which meaning can be processed. For example, a word can be described (and processed) in several modes: orthographic, syllabic, the entire word and its meaning. At the assessment or methodological level, the analogy with the level of processing rationale lies on the relationship between the depth of processing and memory performance. When
higher levels of descriptions are used by the subject when processing the information, the 
memory performance increases: the better the meaning, the better the memory perfor-
mance. This can be observed in initial experiments on level of processing in which the 
depth of processing was oriented. It was demonstrated that subjects who where instruc-
ted to process the meaning of words (e.g. rating the pleasantness of words) had a better 
subsequent recall performance than subjects who were instructed to process the same 
words at a more shallow level (e.g. counting vowels). The similarity with experiments 
using recall performance in order to test if meaning can be better processed with one 
display (e.g. Vicente, 1992a) is evident.

There have been several presentations of the abstraction hierarchy (e.g. Goodstein 
& Rasmussen, 1988; Wirstad, 1988; Vicente & Rasmussen, 1990, 1992; Bisantz & Vicente, 
1994). Each level in the abstraction hierarchy represents a different class of constraints: 
the purpose for which the system was designed (functional purpose), the intended causal 
structure of the process in terms of mass, energy, information or value flows (abstract 
function), the basic functions that the process is designed to achieve (generalized func-
tion), the characteristics of the components and the connections between components 
(physical function), and the appearance and spatial location of those components 
(physical form). The higher levels represent relational information whereas the lower 
levels represent more elemental data (Wirstad, 1988; Vicente, 1992a, Bisantz & Vicente, 
1994). For example, using this hierarchy in describing the DUal REservoir System 
Simulation (DURESS), Vicente and Rasmussen (1990, Figure 6, p. 234) distinguish 
several forms of description of the system: functional purpose (satisfy current demand, 
keep water at desired temperature); abstract function (mass balance: mass source, mass 
inventory, mass sink; energy balance: energy source 1, energy source 2, energy inventory, 
energy sink); generalized functions (cooling and water source, heat and water store, heat 
and water sink, heat source); and physical function (feedwater stem 1, feedwater steam 2, 
reservoir, heater, current demand). One may argue that the description provided by the 
authors is only provided for a simulated and simple system compared to a real process 
control system (a dual reservoir system is not a nuclear power plant), and that the 
presentation of the entire AH is not provided by the authors although the research team 
has conceived the simulated process (the authors explicitly say that they do not present 
the AH). But these two arguments fail to contest efficiently the value of the framework. 
First, engineers can be supposed to be familiar with the use of a similar AH, if not the 
same (see Maddox, 1996). Relatedly, this paper will later demonstrate that in: a some-
what classical description of the functioning of a PWR, one can immediately see what 
describing a PWR at the level of generalized functions means. Second, perhaps more 
important than the explanation of the entire AH used, is the possibility for the reader to 
clearly see in what fashion the displays elaborated or studied effectively reflect the use of 
an AH. This next step, which consists in embedding the hierarchy used in the display, is 
illustrated in Vicente and Rasmussen (1990, pp. 237–238) by making visible, in a display, 
the equation describing the mass balance system in a reservoir of their process. Because 
this display does describe, at least partially, the process at the level of abstract function, 
there is no doubt this constitutes a Physical and Functional display (P + F display) and 
consequently an ecological interface which differs from a classical Physical display (P 
display) presenting lower-level information more in conformity with the location of the 
physical components of the system. Here again, one could criticize this implementation
which does not address the global functioning of the type of system simulated in DURESS: a PWR. However, on the basis of the description of a work situation, we will later present the equation describing the heat exchange between primary and secondary systems in an existing PWR. We will also provide the reader a comparison of two existing displays in this situation and observe the implementation of this exchange in one of the displays (a P + F display). In addition, a number of other features will be observed in the displays and will be helpful in diagnosing that the work achieved by some designers of PWR reactors somewhat follows the logic of the EID framework which consists in proposing not only Physical displays but also Physical and Functional displays. In fact, concerning the step of implementing the hierarchy in the displays, we will see that even a very concrete problem, anticipated in the literature on EID, has been faced and solved in this work situation: the problem of integrating the different process representations one can use in describing a system. For the moment, let us just describe this problem which appears to be a problem of orienting the processing.

2.2. THE PROBLEM OF INTEGRATING THE PROCESS “REPRESENTATIONS”

According to the authors, an efficient design strategy must include the different levels in the tools offered to the process controller. Behind the concept of MultiLevel Interfaces (MLI), different design strategies can be found that aim at integrating the physical–functional representations of the process. It is clear that these strategies [cf. Vicente (1992b, c) and Rasmussen, Pejtersen & Goodstein (1994) for examples of multilevel interfaces and design strategies] provide answers to the problem of the multiple process models that can be used by the operator, namely that of orienting the processing. First, implementing the most abstract levels of process representation improves the interpretation of the state of the system. For example, expressing the abstract function level by means of a mass-energy balance display is important for both normal and abnormal situations since any important alarm will result in the rupture of the principles of mass and energy conservation. Thus, although bar charts directly showing the mass and energy balance in the process necessitate extensive processing requirements, they must, nevertheless, be made operational in the interface as any serious problem will result in the rupture of this balance (Goodstein & Rasmussen, 1988). Second, integrating the physical and functional representations into the interface so that the reasoning is not taken to a deeper level than necessary. Ensuring that the operator can process events at a deeper level is important, as the most critical class of events are those of an unforeseen and unfamiliar nature. Whilst bearing this in mind, reasoning should not be forced to an unnecessary deep level. As the level of processing necessary at any given time for a particular operator is unpredictable, integrating the different representations into an interface is a necessary step. This point is clearly the aim of the ecological approach (Flach, 1990; Vicente & Rasmussen, 1990) and more precisely the aim of Ecological Interface Design (EID) put forward by Vicente and Rasmussen (1990). Faced with what appears to be a problem of orienting the processing—the necessity to implement the higher levels and at the same time the necessity not to force reasoning at a deeper level than necessary—one can use two integration strategies (Vicente, 1992c). A first strategy consists in an integration realized by providing operators with different displays which differ in the levels of description of the process. Operators could view displays with only
A temperature/pressure diagram, also called later in this text a pressurization diagram, does communicate relevant info for the task. Why propose such a tool? In a pressurized reactor, the state of the water in the primary circuit is a fundamental factor in assessing whether the reactor is in a safe state or otherwise. To prevent the primary water reaching boiling point when passing through the core, its pressure is increased to well above the pressure of the boiling temperature in order to create a safety margin. Pressurizing the primary temperature is achieved by heating (pressure maintaining device heaters). Faced with this problem, the temperature—pressure relationship tables must be “in mind” or in front of one (temperature at which the water changes from the liquid phase to the steam phase, depending on the pressure), whilst bearing in mind the need to retain a safety margin. Studies have suggested (Broughton & Walsh, 1981; Beltracchi, 1987) giving the operator a pressure diagram, in other words a diagram showing the temperature—pressure relationship, as well as the permissible operating margin. This is a clear example on the relationship between task and the design techniques used to represent the process at higher levels of description.

2.3. A NUMBER OF PRINCIPLES OF GRAPHIC DESIGN

The mass/energy balance graph of Goodstein and Rasmussen (1988) indeed corresponds to the definition of the “abstract function” level, a level that implies direct display of the principles of mass and energy conservation. Bar charts with a central zero can display these balances.

The temperature/pressure diagram proposed by Broughton and Walsh (1981) corresponds to this same abstraction hierarchy as, in a reactor, a physical component (electrical heating components of the pressure-maintaining device) corresponds to a more abstract function (adding heat to the fluids heat exchanger), resulting in a liquid transformation phase (changeover to the steam state), etc. Chunking therefore explains why a temperature—pressure diagram is often proposed and supplied to the operator for the powering up procedure. However, with this particular technique, it is clear that the description of the process at higher levels in the hierarchy is motivated by the task to be performed.†

Another interface concept is closely related to chunking: the Westinghouse diagram. Be it a mass-energy balance graph, Carnot cycle diagram, Westinghouse diagram, or pressure/temperature diagram, all these interface concepts appearing in the literature correspond to putting into practice higher levels of the abstraction hierarchy, and follow a logic of integrating data into larger units. This first point is important, as a general

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complexity-reducing mechanism that exceeds the specific model used by a particular author, can account for the reduction in load. It should be noted that the abstract function level is, without doubt, the most popular level if the aforementioned interface designs are compared. The introduction of safety-related characteristics also forms part of this level. Here, colour coding is employed to indicate safety aspects, completing the geometric principles used to demonstrate the balances (central zero diagrams, star diagrams, etc.).

These works could be considered as relatively limited. After all, it is true that not every author proposing interface designs refers to current ecological interfaces and the abstraction hierarchy. Nevertheless, one thing remains obvious. As soon as a particular technique is introduced into the interface to represent and to express factors deemed important to the general functional purpose and the general functions performed by the controlled process, we assume that it can legitimately be stated that the interface uses the abstraction hierarchy, and that it concentrates on the higher levels of this hierarchy. Thus, numerous technical proposals involve applying higher levels of the hierarchy whereas the concept is not stated. This comes across clearly as soon as authors present their reasons for proposing several interfaces and display techniques: the Configural Display, which “represents high-level constraints of the domain through the relationship among the low-level data that define the constraint” (Bennett et al., 1993, p. 72). Thus, the polar star (Woods, Wise & Hanes, 1981) integrates the values of more than 100 sensors to represent the state of the process; the Representation Aiding Technique which, to assist anticipation behaviour, proposes helping the operator to assess “where the level is, what factors are influencing the level (Shrink/swell vs. changes in the mass balance), and where the level will go given these influences and possible interventions” (Bennett et al., 1993, p. 77); the Compensated Steam Generator Level put forward by Bennett, Woods and Haley (1986) is closely related to the higher levels of the abstraction hierarchy, although this technique is traditionally considered as a product of the representation aiding technique; the Integral Display or Object Display is also an example of this logic (Carswell Adapthya, Klaver, Kancler, Dolan & Wickens, 1987; Jones, Wickens & Deutsh, 1990; Elvers, et al. 1993).

We have defended the idea that the principle of depth of processing plays a significant part in the interface designs having recently appeared in the literature. This observation, which clearly applies to ecological interfaces and to a greater extent industrial interface design, could, undoubtedly, be applied beyond the industrial sector (cf. current work on intelligent interfaces, demonstrative programming). However, let us limit ourselves to the industrial context and to the type of process often discussed in the literature: the pressurized water reactor. If the analysis just presented is even partially correct, this same willingness to act on the reasoning should be found in the analysis of a situation concerning the operation of a pressurized water reactor. And here we may even find the application of the information display techniques presented in the literature. Some proponents of the ecological approach of human–machine systems (Kirlik, 1995a) and some commentators on ecological interface design (Maddox, 1996) seem to assume that designers do not wait for applicable psychology to emerge before making design commitments. Can design commitments observed in a work situation be shown to be consistent with the general goal and technical features proposed in the literature? The subsequent section will provide at least partial evidence with this idea.
3. Analysis of a pressurized water reactor operating situation

In this section, the presentation of an existing situation is provided as a demonstration of the fact that the theoretical and technical principles reviewed and coordinated by referring to the logic of depth or processing are relevant for complex situations such as a PWR reactor. First (Section 3.1), a simple academic presentation of the studied controlled process will directly show what describing a process like a PWR at the generalized function level means. In addition, the distinction of the two main states a reactor has will be helpful in understanding that the use of an AH and its implementation in effective display work situations will probably be state-specific. Important parameters to be monitored, mass and energy balances that should be assessed, etc., change a little as a function of the state of the process. Consequently, one may not search for a complete and stable AH which has been implemented but rather be able to diagnose, in relationship with a given context (full operating conditions, start-up operations, etc.) to what extent the proposed or available displays encountered are more or less committed with the presentation of the process at the functional pole or at the physical pole of the abstraction hierarchy. This sort of analysis is provided in the observed situation for a given context: when the reactor is critical and more precisely in the powering up state. Second (Section 3.2) when the reactor is critical and more precisely in the powering up state, we show that the distinction between physical and functional presentation applies to the three different displays available to operators in an existing situation. The displays can be differentiated on the basis of their physical—functional nature and one of them can be characterized as a $P + F$ display. In addition, after comparing the characteristics of the displays, we will see that the full instantiation of an AH in this $P + F$ display has not been achieved because the way the problem of integrating the different process representations has been solved makes use of the two integration strategies previously discussed in literature.

3.1. THE CONTROLLED PROCESS

A definition of the process illustrates the general functions that correspond to the abstraction hierarchy (cf. the hierarchy of Rasmussen, 1985). We highlight some of these general functions in the following definition: heat production, primary fluid pressurization, heat exchange, secondary circuit feed are indicated in italics.

3.1.1. Principle of operation of a pressurised water reactor

The fission of uranium releases calories. These calories are evacuated by the water crossing the fuel elements. The water, which is maintained under pressure to avoid its boiling, transfers the heat to a secondary fluid in an exchanger–evaporator. The secondary water is reheated and transforms into steam when the primary water travels along the exchanger pipes. The steam formed in the exchanger is fed via collectors to turbines that transform the thermal energy into mechanical and electrical energy. The steam that has been used is recovered and condensed by a cold source (the condenser pipes are sea-water-cooled in the case of an on-board boiler plant). The recondensed water is recuperated by means of pumps that send it back to the exchanger where it is again transformed into steam (Figure 1).
FIGURE 1. Schematic diagram of a pressurized water reactor. The diagram shows the general components forming the energy production cycle. As shown in the diagram, this cycle comprises two independent cycles. In the primary circuit, the water remains in the liquid state, and the sequence is 1-2-3-4-5-1. The secondary circuit corresponds to sequence 4-6-7-8-4 and is dual phased: the water changes to the steam state on account of the heat transmitted by conduction at the steam generator tubes; it then returns to the liquid state after passing through the condenser.

The system studied is a compact-type pressurized water reactor, the steam generator being located on the reactor itself. In the case of on-board reactors, this provides significant space saving.

Note that the provided definition does not differ from a definition one could derive from other presentations or even technical manuals in the engineering literature. A simple highlighting of generalized functions in this definition demonstrates that engineers can be supposed to be familiar with the use of the abstraction hierarchy in describing a PWR (at least for one level of description).

3.1.2. The reactor states
A reactor has two main states.

- Non-critical. The core produces no fission, the reactor is shutdown, and there is no production of fission neutrons. This situation encompasses the states of cold stoppage hot stoppage in reduced conditions and hot stoppage in nominal condition.
- Critical. The core produces fission, the neutron population is stable and the reactor maintains the neutron population alone. This situation includes the critical hot
stoppage state (transitory step between stoppage and start-up), and powering up state. The use of steam characterises the powering up state.

The process differs for each reactor state. Depending on the state of the reactor, both the parameters of the system and their operating mode change, as does the means of accessing the parameters. As regards changes in parameters, the powering up state is characterized by the primary–secondary heat exchange being in operation, and the supply of steam to the turbines. However, a parameter such as the secondary-circuit steam flow, which characterizes the general functional purpose for which the system has been built (to supply a source of energy satisfying the demand), is absent in all other reactor states. On the other hand, the absence of the primary pressure parameter, in other words no primary-circuit pressurization, characterises the non-pressurized cold stoppage situation.

Depending on the reactor state, the operating mode of the variables changes. The main systems for automatically regulating the parameters to be monitored (pressure-maintaining device level, primary pressure, steam generator level) may or may not be in operation. This leads to a variable ratio of the role played by manual parameter control to that layed by manual intervention replacing automation devices. In addition to the change in the “operating-monitoring” ratio, safety systems may or may not be present depending on the configuration of the process.

Finally, access to parameters differs according to the reactor state. The primary temperature is a parameter that is permanently monitored regardless of the state of the reactor. However, in the reactor shutdown state, the sensitivity of the primary temperature measurements differs from the other states—a phenomena highlighting the variations in the “degree of control proximity”. A measurement breakdown system (monitoring different points in the vessel in addition to the average temperature measurement) allows these measurement sensitivity differences to be compensated for with respect to the other operating states.

These few factors would seem to suggest that both the task and operator activity are not the same from one reactor state to another. Although the central operating parameters remain more or less the same, it is more appropriate to consider the operating and monitoring requirements state by state, since both the parameters and their operating mode change, and the degree of control proximity of a variable that is common to all the reactor states can also vary.

In close relationship with these variations in task and operator’s activity, the fact that the process differs as a function of reactor states shows that a work domain analysis with the abstraction hierarchy would be fruitful, at the implementation step, if the analysis is state-specific. For example, because powering up is the only state that corresponds to the general functional purpose of the reactor, namely to supply a quantity of energy (steam) compatible with the energy requirement, there would be no need for applying the hierarchy when describing the steam generator. More precisely there would be no need for presenting either directly the relationship between vapour produced and the water entering the steam generator (P + F logic) or the steam and the water volumes separately (P logic) if the reactor is not in full operating conditions. Powering up is the reactor state that is used to describe the operating task and the monitoring requirements in the analysis of the operating task. This state is also used in the discussion of the physical—functional characteristics of the displays.
3.2. ELEMENTS OF THE ANALYSIS OF THE OPERATING TASK

3.2.1. The operating task

Powering up is characterized by supplying steam to the front machine via isolator valves, and the task of the operator primarily consists of the following.

- Setting the primary pump (Ppe P) and feed pump (EPAP) to the power of the boiler plant and the steam distribution configuration; the power output of the boiler plant.
- Monitoring the stability of the primary temperature (Tm), maintained by the setting of the primary temperature, and complementing the temperature regulation automation system as necessary; monitoring the steam generator level (VN), maintained by the corresponding automation system, and complementing it as necessary; monitoring the stability of the primary pressure (PP), if this is not controlled by the pressure regulator (RPP).
- Monitoring the physical quantities vital to correct system operation and, more particularly, the flows (NF, TX NF), the primary temperature (Tm), the primary pressure (PP), and the levels at the pressure maintaining device (PN) and the steam generator (VN); monitoring the conformity of the positioning diagram of core mechanisms; checking the availability of the control instrumentation (feeds, corrective actions) and the coherence of the readings given by the instrumentation.

In addition to the operating task itself, the operator has other tasks to accomplish. These include assessing, for example, the quality of the primary water every 24 h and periodically reading the parameters. He is also involved in the training of naval personnel as the situation studied is a land-based prototype of an on-board reactor.

Having presented the operating task—what the operator should do—in the context of powering up, then the question of whether engineers have or have not used, and more important here, implemented an AH can be examined correctly. Remember that there is no need to presenting either the steam–water relationship (P + F logic) or the steam and the water volumes separately (P logic) if the reactor is not in full-operating conditions. With these facts in mind, we will see that an AH has been used. A problem occurring as a result of the use of an AH, the problem of integrating the different representations of the process into the operating interfaces (Vicente & Rasmussen, 1990), has been evidently faced here by the engineers. This problem has been solved by one dominant mean of integration within the two modes suggested by previous work (Vicente, 1992b): different displays which differ in the physical–functional dimension co-exist. In addition, further evidence of the use of the AH is provided by showing that the design principles we have recycled as means for presenting information at the abstract level function are implemented in a display which can be considered as a P + F display. These different observations reflect the use of a design strategy which can be retrospectively used as an indirect demonstration of the applicative value on ecological interface research.

3.3. THE OPERATING INTERFACES: INTEGRATING THE REPRESENTATIONS OF THE PROCESS

An important question in task analysis has been to identify the different information display systems and their characteristics. Here, this question is treated in a specific manner, based on what has been described in the first part of the paper: the characteristic
used to differentiate the devices, namely their physical–functional nature. Are there
information display systems that differ in the way the process is presented, in other words
devices that differ in their physical–functional axis from the model generally used in the
design of interfaces for pressurized water reactors? If this is so, how is integration
achieved: several separate devices or one device integrating the different display modes?
Answering these questions means (at least) looking into: (a) To what extent the devices
present elementary parameters, conserve the spatial location of the components, and use
alphanumeric codes. This is the physical pole. (b) To what extent the devices present, in
addition to the elementary parameters, complex variables without respecting the spatial
location, and use geometric properties and colour. This is the functional pole. In the
situation analysed, three devices (see Figure 2) can be distinguish.

**Data presentation system:** this device, which includes an instrument panel screen to
present overall views of the different reactor states and a message screen, is designed in
accordance with reactor logic. In the instrument panel screen, one observes a representa-
tion of general mass and energy balance functions that employs central zero diagrams,
colour codes for the various safety aspects or even a pressurization diagram. The
organization of information does not always respect the logic of the spatial location of
the components and favours functional organization. Typically, further description of
this display (in Figure 4) will show that parameters are both displayed in a quantitative
(numeric values) and qualitative manner (barograph, thresholds). The emphasis on
functional information appears also at the level of the warning labels screen of the DPS.
In the warning labels screen, parameters are displayed in a qualitative manner (e.g. PN
HIGH) rather than by indicating the numeric value of the parameters. This emphasizes
again a greater or lesser depth of processing. In addition, to relate the state of a para-
meter described qualitatively (high, low, insufficient) with the corrective action triggered
on the basis of the state of the parameter is to simultaneously display two types of
information that beforehand were found dissociated in the control desk. The structure of
any message in the warning labels screen is “automatic action: event”. For example,
“HEATERS ON: PN HIGH”. Presenting the link between two pieces of information
that the operator had to bring mentally together previously is what warning labels do.

**Control desk:** more traditional, this corresponds to the synopsis of control rooms, and
presents somewhat elementary variables. It respects the spatial location of the compo-
nents. Here, the level of presentation is that described in studies on control rooms,
namely presentation by a galvanometer. Typically, in this case, numeric values are
displayed.

**Display selection keyboard (DSK):** this device groups the standard variables displayed
by galvanometers but also gives access to more detailed information as the rotational
speed of a pump (RPM). This device offers the most detailed level both on the component
concerned by the information (it displays components not present at the control desk),
and in the way of displaying variables indexed elsewhere (more accurate variable values).

The operating state devices are distinguished in the way they present the information.
The proportion of “physical” and “functional” presentation differs according to whether
the DSK, the general control desk, or the DPS is consulted. Figure 2 shows that the
device at the top of the physical–functional hierarchy (DPS) and the one at the bottom
(DSK) are integrated at different locations on the general control desk. The work
situation is therefore characterized by the strategy of representation integration at
Figure 2. The three devices at the operating position. The figure shows how three levels of description of the process are available for the operator controlling the process. The lower level (level 1) consists of a Display Selection Keyboard which presents very precise physical information on the parameters in a numerical format. The numerical information is also provided in the different parts of the Control Desk (level 2). Typically, in this physical presentation, galvanometers are used in displaying the value of parameters. Parameters are displayed in conformity with the position of spatial components (primary system, primary-secondary, secondary system). All these features are also evident in the central panel for the control desk depicted in the figure. The higher level of presentation (level 3) is the Data Presentation System in which more emphasis is placed in functional presentation by means of (a) a warning labels screen, (b) the DPS display in which the important parameters are also presented in analogical format. This occurs for each process state: the DPS display thus consists of several central panels of the DPS. Figure 4 provides a more precise description of what the DPS display looks like for powering up.
differing description levels, a strategy based on the presentation of the different devices. Examining the organization of the most “functional” tool (DPS), it would appear that there has also been a willingness to integrate the physical—functional axis within the same device. This is another strategy for integrating the representations, and another way of resolving the problem of the necessary coexistence of differing points of view on the process. This integration within the same tool was not taken to its full extent in the version examined. A certain number of circuit views associated to views of each reactor state, should have been developed. However, only three of these circuit views can be consulted at present. The presence of other devices, notably the DSK, in widespread use given the specific operations that the operators have to perform frequently, may explain why integration into the same devices was not taken to its full extent. Still, the work situation also allows the integration of physical and functional variables within the same device to be observed. The DPS provides several examples of this, notably at the instrument panel level. First, when bar charts employing the principle of a zero base line are constructed to display the mass and energy balance of the controlled system (Goodstein & Rasmussen, 1988), this is a way of presenting the system with a high abstraction level. The DPS makes use of this logic, for each reactor state. Second, when temperature and pressure values are presented together, as is the case in the pressurization diagram, one of the possible techniques for displaying functional information is indeed being used. This is the principle put forward by Broughton and Walsh (1981). The DPS display makes use of this principle which is observed to be useful in other reactor states than powering up conditions. Further description of the DPS, at the instrument panel level, will be provided in Figure 4.

To sum up, devices that differ in their physical—functional aspect are available in the operating situation. The two previously described types of integration are present: integration by means of different tools, and integration within the same tool. The predominant integration mode in the situation analysed appeared to be the former. Having seen how the problem of integration of physical vs. functional presentations has been solved in this situation, further description of two displays that demonstrate variation on the physical—functional dimension should be added.

3.4. COMPARING THE CENTRAL PANEL AND THE DATA PRESENTATION SYSTEM

The central panel of the control desk (displayed in Figure 3) is situated in zone 5 of Figure 2. It is an overall view (also termed “zone flash”) that includes several characteristics allowing it to be considered as “physical”: respect of the spatial location of the components (the view is a schematic diagram of the compact pressurized water reactor), standard information coding (that of the general control desk). In contrast, the DPS powering up instrumentation panel (displayed in Figure 4) places greater emphasis on the functional presentation of parameters, and on the meaning of the situation; instruction values, thresholds, combinations of variables directly showing the balance in the system. Comparing these two devices allows variation of the physical—functional dimension.

Comparing Figures 3 and 4 shows why the DPS view can be considered as a functional display with respect to the control desk panel: presentation of instruction values, thresholds, combinations of variables directly showing the balance in the system. Let us
take the case of ΔTGV, which expresses the heat exchange between the primary and secondary. Presenting this parameter is to present the energy balance in the process (Core Output Temperature—Steam Generator Output Temperature); the DPS displays this parameter (see ΔT in Figure 4) whereas the zone flash does not. Of greatest interest is, undoubtedly, that this variable can be found by the operator from elements available to him (TSC and Tm). Indeed, taking into account the two equations below, comparing the DPS with the panel comes down to comparing a case where a high-level variable is calculated and presented to the operator by the interface, and a case where this variable must be calculated for use in the analysis. It can easily be verified that, as TSC and of Tm are displayed on the panel, then calculating ΔTGV is equivalent to resolving an equation with one unknown: to find TSGV in equation (1):

\[
Tm = \frac{\text{TSC} + \text{TSGV}}{2}, \tag{1}
\]

\[
\Delta \text{TGV} = \text{TSC} - \text{TSGV}. \tag{2}
\]

The DPS displays other energy balances (NF – WS) or mass balances (SQ – VQ) not present on the panel. We must emphasize why the DPS is presented here as a P + F display and not simply presented as a multilevel display. In a recent discussion on what constitutes or does not constitute an ecological interface—see this discussion in Maddox 1996) and Vicente, Christoffersen and Hunter (1996)—it has been argued that a given multilevel display can be characterized as a P + F display IF it implements the abstract
FIGURE 4. The powering up control panel of the DPS. The values of important parameters are displayed without reference to the spatial position of physical components. They are complemented by barographs in which: the central zero technique indicates the instruction value (solid line in the middle), thresholds (dashes on the right) are indicated, often related to safety margins. These principles are applied in designing the energy or mass balances in a task related rationale: typically, here, for powering up, the relationship between the water entering the steam generator and the vapour produced by the steam generator is displayed (SQ-VQ). This is a mass balance.

function level of description. The DPS display, which was put into operation assuming that better access to meaning was provided, clearly meets his criterion.

We have just seen how, in a work situation, the abstraction hierarchy can be found behind the interfaces proposed for controlling the process, how the question of integrating the different representations of the process is resolved (with both types of integration strategy), and how the different graphic techniques put forward in the literature to provide a better understanding of the situation are indeed applied. It is in this type of situation that the hypotheses advanced in the literature should be tried and tested. Indeed and this is one point that we are about to deal with in the conclusion, one has to accept that the advantage of physical and functional information displays over physical displays—better access to meaning—has not actually been demonstrated with memory recall performance. As far as assessing these tools is concerned, the role played by the principle of the depth of processing assumes accepting certain results. Furthermore, these
results must be obtained in certain conditions. Some of these conditions, implemented in
the empirical studies we have conducted in the depicted situation (Terrier, 1996; Terrier
& Cellier, 1997; Terrier et al., 1997, 1998) will be briefly discussed in the conclusion.

4. Conclusion

Nowadays, ergonomics studies on interfaces have cognitive ambitions. Moreover, the
concepts of support and compatibility, already well established in ergonomics, are being
employed with adjectives: cognitive supports, cognitive compatibility. The approach
adopted in the majority of cases in sensitive industrial sectors consists of constructing
interfaces on the basis of an analysis that determines the crucial variables, by applying
different principles of organization and synthesis to the variables displayed to the
operator. Experiments are then undertaken to verify whether an interface “reduces the
mental load”; in other words to verify that an interface allows better access to the mean-
ing and an enhanced perception of the state of the process. Papers recently published on
operating interfaces in the nuclear sector are good examples of this willingness to act on
reasoning and of this approach. These studies indeed have three characteristics, and the
empirical situation that just been described fits into this framework.

Firstly, studies adhere to the idea that an efficient interface is one that gives informa-
tion on the process both on a basic level, that of physical parameters, and on more
abstract levels of reactor description, that of more general functions (Vicente & Rasmus-
sen, 1990, 1992). It is true that describing a process by means of an interface can be done
at different points along a “functional—physical” axis. Should the interface display
together variables corresponding to the same function? If so, primary—secondary heat
exchange will be displayed, or even the ratio between the exchanger-evaporator inlet
water flow and the outlet steam flow (functional pole). Or, should the information be
displayed separately as it does not correspond to the spatial location (physical pole). The
response put forward is that it is necessary both to give the information on an elementary
level and also allow a direct perception of the mass or energy balances through different
information codes. Typically, in the work situation we have described, the difference
between three displays has shown an example of this first characteristic.

Secondly, studies propose information display devices using different codes
(Broughton & Walsh, 1981; Beltracchi 1987, 1989; Goodstein & Rasmussen, 1988;
Vicente, 1992b; Bennett et al., 1993). This means coding the information in such a way
that the interface also presents the state of the process at the most functional levels. To
achieve this, the studies have suggested using geometric principles (star diagrams, central
zero diagrams showing the energy and mass balances in the process, pressurization
diagram) and colour as a means of coding safety-related aspects. The reasons put
forward for proposing these codes concern safety and ease of operator processing. In the
work situation we have described, the comparison between two displays has shown an example of this first characteristic.

Finally, studies propose information display devices using different codes
(Broughton & Walsh, 1981; Beltracchi 1987, 1989; Goodstein & Rasmussen, 1988;
Vicente, 1992b; Bennett et al., 1993). This means coding the information in such a way
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zero diagrams showing the energy and mass balances in the process, pressurization
diagram) and colour as a means of coding safety-related aspects. The reasons put
forward for proposing these codes concern safety and ease of operator processing. In the
work situation we have described, the comparison between two displays has shown how
functional levels of description of the plant status were more directly communicated with
one display. Also a number of codes suggested to implement the higher levels of
description are implemented in this situation: typically, the central zero diagram is used
at several locations in the DPS screen for powering up (see Figure 4 for further
description). Another design technique which cannot be seen in Figure 4 because it is
located in other pages is the pressurization diagram.
Thirdly, experiments have attempted to validate tools that have been built (Vicente 1992a; Moray 1993). In the experiments in question, diagnosis and memorization were employed to verify that the new interface reduces the load more than the old one. Hence, to verify that one interface allows better access to the meaning of an event than another interface, the authors had two groups of subjects study the same scenarios. Then, the supposedly better interface was examined to see whether it provided a better diagnosis and better parameter memorization. Using a memory task in conjunction with the diagnosis is founded on a well-known principle in psychology and ergonomics, namely the principle of depth of processing: one memorizes better when one processes the meaning of the information rather than the superficial aspects of the information presented. It is therefore relevant to use memory tasks to test the advantages of interfaces that integrate both physical and functional aspects, as these are information displays that are supposed to lead to deeper processing.

In the work situation presented, this empirical logic could be used. We have seen that one way to vary the factor of interest (Physical/Functional information) is to present either the information contained in the central panel of the supervisory control desk (physical view), or the instrumentation panel dedicated to the powering up (physical and functional view). Even, the work situation depicted has interesting characteristics for a test in ‘ecological conditions’. Studies have, for the most part, been conducted in the laboratory, as indicated in the resulting articles (Bennett & Flach, 1992; Vicente, 1995), and it is difficult to find studies that have clearly shown that an interface embedding the abstract levels of the hierarchy gives better access to the meaning in ecological conditions: for a non-simplified process, with the participation of experienced operators, who are familiar with the compared displays. Here, these conditions could be taken into account when comparing the two displays depicted (Figures 3 and 4). With the highly trained operators who conduct the process, who are familiar with these displays, the advantage of the interface showing the semantics of the domain, if any, could possibly be lessened. There would be another important motivation for conducting such an experiment in an ecological context. An important question is to know whether the advantage of these tools has actually been observed. This would not appear to be the case because, considering the logic underlying these works there are certain results that should be observed in terms of recall quality. If a “physical and functional” interface really leads to a better understanding of the situation, a better recall should be observed for this interface on account of the principle of depth. However, a more accurate result should also be obtained, namely an interaction between the significant or insignificant character of the scenario and the type of interface: the “physical and functional” interface provides a better mnemonic performance for significant scenarios only. This result, which is vital for corroborating the central assumption of the EID framework, has not yet been obtained although it has been predicted (Vicente, 1992a).

The ecological conditions we have just outlined were present in a first experiment we have conducted in this situation (Terrier et al., 1997). The experiment allowed two overall views (Figures 3 and 4) to be compared. These views which have been distinguished by their physical–functional aspect, could also be legitimately compared because they present a common series of relevant variables for analysing the powering up situation. More precisely, in relationship with the operating task presented here (in Section 2), a more detailed analysis allowed us to control that a series of important parameters to be
controlled were available in both views. These common parameters could even be distinguished in three levels of priority (high, intermediate, low). The views, known to the operators, were compared as a function of diagnosis and memorization, within a context where operating experience has a role to play. The results on memory recall performance showed that a clear advantage of a P + F display in terms of access to meaning could be observed for skilled operators. Indeed, a significant scenario*display interaction on memory recall performance was obtained consistent with the depth of processing rationale. The P + F display lead to a better access to meaning; memory recall performance was better with the P + F display ... for meaningful scenarios, not for non-meaningful scenarios. This result, obtained for the first time, has important implications for EID. In conformity with the emphasis we have placed in task analysis in this paper, this was obtained while taking the task into account: the scenarios were either meaningful or non-meaningful ... for powering up conditions, not in general. We assume that task-related dimensions could be and perhaps should be taken into account when testing the advantage of new artifacts. Indeed, results on memory performance have also provided another interesting result in the same vein which is consistent with the depth of processing principle as discussed in the introduction (information can be more or less at hand for the task to be performed and consequently more or less memorized). A second look at the data showed that, within the pool of important parameters for powering up, higher priority parameters were more recalled than lower priority parameters, this result being observed for the two displays (Terrier et al., 1998). To sum up, a precise result was obtained showing an advantage of the P + F display in terms of meaning. And this result was obtained while more task analytic dimensions were taken into account: the scenarios were either meaningful or non-meaningful in powering up; with both displays, a model of priority within the important parameters for powering up could be partially validated. Other experiments have then been conducted on memory performance in this work situation, showing now limits on the use of memory recall paradigm. For example, in a second experiment (Terrier & Cellier, 1997) the ecological assessment of a specific feature of the warning labels screen called for the use of another memory paradigm. It is our contention that work situations could be seen as a fruitful context for assessing the realism of theoretical and technical proposals in the literature. A point abundantly discussed in this paper. However, after evidence for proposals usually restricted to the laboratory has been found in a work situation, work situations could perhaps also provide ecological conditions that could be taken into considerations when testing these proposals.

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