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THE COGNITIVE ASPECTS OF THE ENGINEERING DESIGN ACTIVITY – A LITERATURE SURVEY

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ABSTRACT

This literature survey aims at representing the current research on the cognitive aspects of the design activity, with an emphasis on problem-solving processes. The study is based on the selection of about sixty papers and books on the subject. The principal parameters of the study were defined as follows: general topics of the works, objects of the works, cognitive approaches, research results, study methods. The findings from this survey are: Most of the studies concern design theory, and then design support and education; They focus mainly on the conceptual design phase; The foremost cognitive aspect studied is problem solving, but knowledge, imagery and memory are also considered; The results of the reviewed papers confirm the validity of prescriptive methods for the design process, but there is a felt need for acknowledgement of the design activity constraints induced by cognitive limitations; The methods employed in most experiments are based on verbal protocol analysis and sketch analysis. The most important findings of this survey are that research should be extended to new areas, such as: Research on the cognitive aspects of the designer in the embodiment and detail design phases; Implementation of the research findings in current design practice, to improve the design process; Research of the origins of expert knowledge.

KEYWORDS

Design process, conceptual design, problem-solving process, cognitive aspects, verbal protocol analysis, literature survey.

1. INTRODUCTION

As summarized in Pahl, G. et al. (1999b), when engineering design stopped being considered as "an artistic activity", design methodologies could be developed. Special efforts have since been striving towards normative design procedures, aiming to rationalize and optimize the development of technical artifacts. Methods have been developed for the conceptual as well as for the embodiment and detailed design phases; requirements for education, experience, knowledge, reasoning and problem solving ability of the designer have been stated (e.g. Hubka, V., 1976/1982; Pahl, G. & Beitz, W., 1977/1996[1]). This has resulted in substantial improvements in terms of costs, shorter lead times and higher product quality. However, systematically or based on best practices, present methods have been focusing on the product technologies, thus neglecting the importance and impact of the human factor — the designer. Initiated by the increased importance of the cognitive sciences, from psychology to artificial intelligence, the designer's way of reasoning has attracted increasing attention during recent decades. It is a widely accepted assertion that the very nature of the design process is considered to be a problem-solving activity: understanding the task, generating solutions, evaluating and selecting them.

This paper is a survey that aims at representing the state-of-the-art of the research on cognitive aspects of the design activity. The designer's problem-solving process is emphasized. The method for the survey is briefly described in a first part. This is followed by a summary of the relevant problem-solving aspects in

[1] The second date of two separated by a slash mark indicates a reference where English translation is available.

design. In the third part, a representation of the current research in this area is developed, and a review of recent years of conjoint research between engineering design and cognitive psychology is presented. The last part reflects on the findings and proposes future paths of research.

2. METHOD

A loosely structured method was adopted for this review, similar to that used by Krishnan, V. & Ulrich, K. T. (2001) in "Product Development Decision: A Review of the Literature". As a first step, we built a superset of papers related to cognitive psychology and design. We did this by searching in the university database Elin by using keywords. Elin includes among others the following journals and conferences: *Research in Engineering Design*, *Design Studies*, *Automation in Construction*, *Frontiers in Education Conference*, *Management Science*, and the *Journal of Product Innovation Management*. The titles, then the abstracts, of the papers found narrowed the number of papers to a first set. Next we browsed the table of contents of the 8 journals that appear most frequently in the selected articles. Finally, the reading of each paper led us to the referenced articles that seemed to be of importance for the domain study.

Parallel to this task, the findings in cognitive psychology relevant to the problem-solving process in the design activity were picked out, both from the cognitive psychology literature (e.g. Sternberg, R.J., 1994) and from engineering design works (e.g. Pahl, G. & Beitz, W., 1996, p. 46-60). This is presented in the next section.

The articles that were found relevant to the survey were classified as follows: 1) The scope of the work; 2) The design process concerned; 3) The models from cognitive psychology used; 4) The findings; 5) The research methods used. They are presented in section 4.

3. PROBLEM-SOLVING PROCESS (PSP)

The aim of this section is to summarize the well-recognized findings on problem solving in cognitive psychology that are relevant to the study of the design activity.

3.1. PSP in cognitive psychology

Since psychology became a science, problem solving has been studied frequently; Dominwski, R. L. and Bourne, L. E. (1994) give an overview of the research up to the 60s, whereas Ericsson, K. A. and Hastie, R. (1994) give insights into the involvement of cognitive psychology in problem solving.

The breakthrough in the study of problem solving in psychology occurred when Newell, A., Shaw, J. C. and Simon, H. A. (1958) proposed a computer program for modeling human thought. Formalized in Newell, A. & Simon, H. A. (1972), problem solving took the shape that serves as a basis now for most of the modeling: the problem, a gap between an initial state and a goal state, can be represented as a problem space (containing all the problem states) that must be searched using methods or techniques of problem solving: algorithms and heuristics. While an algorithm is a rule that correctly generates the solution to a problem, given sufficient time and effort, a heuristic "refers to a rule of thumb or general strategy that may lead to a solution reasonably quickly" (Kellogg R. T., 1995). Hubka, V. worked on heuristics in design (see Hubka, V. & Eder, W. E., 1992/1996), illustrating general techniques. Todd, P. M. & Gigerenzer, G. (2001) argue that simple, everyday-life heuristics may lead to good results in less time than complex ones; however, dedicated heuristics remain more efficient.

In conceptual design, strategies often enhance the generation of numerous ideas by using the so-called creative solving processes (see VanGundy, A., 1981); this is underpinned by the use of a systematic approach, decomposing the technical system, looking at a great number of potential sources of concepts, then trying to combine the concepts of each subsystem. The problem-solving process in conceptual design is of the "task-understanding-solution-generation-evaluation" type, because emphasis is placed on the information search (the problem is ill-defined in conceptual design), the great number of alternatives that are generated and the difficulty and importance of evaluating them.

Basic rules (*simplicity*, *clarity* and *safety*) and principles in embodiment and detail design are heuristics. Although equivalent, a PSP model that underlies the embodiment design may rather be an "analysis-synthesis-evaluation" type of process than "task-understanding-solution-generation-evaluation" described above. This model focuses on the rigorous study of all elements of the problem and their interrelations (analysis), and on the combination, or composition, of sub-solutions, to create an overall functioning system (synthesis). This indicates that the abili-

ties and experience required in problem solving can differ for embodiment design, detail design and conceptual design. The problem space is different as well: the initial and goal states of an embodiment design are relatively well known (even better in detail design), because of the existence of the artifact concept. In conceptual design, they are often unclear and have to be constructed by the design team. The solution in embodiment design and detail design has a different structure: many features (all in detail design) of the product have to be fixed, not found, and designers no longer work with intervals of product parameters value.

3.2. Knowledge

Knowledge elements, and knowledge retrieval and use, are of major importance in design.

The knowledge elements are the mental representations or sets of mental representations of what we know about objects or events. Many structures of the elements have been developed. Models for objects are the classification of similar instances in categories. The most familiar have been the prototype (a concept with a number of separate features, each with some weight; each instance can be recognized comparing its features to prototypes), combined with 'the exemplar view' (explaining the prototype-like effect: recognition of similar instances that share only a few features with the prototype). On the design level, Condoor, S. S. et al. (1992) have exploited this view. An extensive review of concepts and categories in cognitive psychology has been made by Ross, H. R. & Spalding, T. L. (1994). This aspect affects the learning in design that constitutes the creation of categories.

More complex models have been developed that include events associated with objects. The most broadly used is the schema (the *prototype* is a kind a schema; see McNamara, T. P., 1994, for other models). Many definitions exist; schemata can be seen as structures containing sequences of events, "prepackaged expectations and ways of interpreting" (Chafe, W. L., 1990, p. 80 in Kellogg, R. T., 1995). In the pattern-action rules, the basic thinking processes that operate during problem solving (like induction and deduction) are elementary operations that allow manipulation of knowledge elements. The skilled problem solvers, or experts, proceed in a different manner: they rely on previously memorized solution schemata (i.e. particular memorized procedures). When a person is faced with a problem, and recognizes that it is a specific case of a general, previously encountered, problem, that person then simply applies the learned rules that will lead to the solution, without working backwards as novices do (Hunt, E., 1994).

The distinction between novices and experts is stressed here. It would be of great importance to look at how experts use the basic rules, guidelines and principles of embodiment design. In contrast to conceptual design, where knowledge has to be broad and interdisciplinary, the knowledge in embodiment and detail design is very specific. That can play a role in prototype formation, and in knowledge retrieval and use.

Another important matter related to knowledge is the mental imagery, concerned with the issue of how information is represented in memory (Solso, R. L., 1988). In design, especially form giving, the visual aspects are important, and progress in that area will stress development based on sketching, for example. This connects to knowledge retrieval, which occurs through pattern recognition, where visual information is of great importance. Recognizing forms and attributes, it is possible to come back to the prototype of the observed instances (Solso, R. L., 1988).

3.3. Complementary domains in cognitive psychology

Considered as a high-level cognitive process, problem solving is thus related to many other fields, especially memory, thinking processes or pattern-action rules, intelligence, and creativity. Some of them, interesting for a design theory, may however be specific neither to embodiment design nor to detail design.

Thinking processes concern mainly the studies of induction (Bisanz, J. et al., 1994) and deduction (Rips 1994). Research studies in intelligence are still in a maturation phase (Solso, R. L., 1988). These areas are still on a too abstract level for applications concerning the design activity.

Memory models are very important for problem solving because they explain some limitations of the human being. If the long-term memory has a virtually unlimited capacity, the short-term memory has a buffer that cannot contain more than 7±2 items at a time (Miller, G. A., 1956), and for a limited moment, around 12 s. This explains the knowledge model of schemata – a schema being considered as one item – and also emphasizes the importance of external sup-

port to memory (e.g. sketches, writing, speaking). These supports have been the subjects of extensive research in conceptual design (especially sketching in architectural design), as presented in the following section.

Creativity is "the ability to produce work that is both novel and appropriate" (Lubart, T. I., 1994[2]). In that sense, creativity is needed and common to all design activities. There is no unified theory about creativity, nor has great progress been made during the past twenty years (Solso, R. L., 1988). The most generally accepted creative process model is that of Wallas, G., from 1926, who describes it in 4 stages: 1) Preparation: formulating the problem and making initial attempts to solve it; 2) Incubation: leaving the problem while considering other things; 3) Illumination: achieving insights into the problem; 4) Verification. Even if the internal mechanisms of creativity remain unknown, numerous studies have been done in design in order to provoke and model creativity. If creativity is needed at all stages of the design process, things change when we are considering first the relative importance of the creativity for each phase, then the 'quantity' of creative findings. On a conceptual level, creativity will be emphasized: the start of a new design comes from a need, i.e. a lack, expressed by a client or the company itself, which only something new can fulfill. Moreover, in order not to focus on one solution, many concepts will have to be found. On the other hand, one of the guidelines of embodiment and detail design is the re-use of designs or use of standards, for reasons of performances, delays and costs (and that is confirmed by the basic rules of simplicity, clarity and safety). Matousek, R. (1963, p. 65) recalls that proven designs are well thought out and changes must be undertaken with full knowledge of facts. Thus the task of the designer is more to focus on retrieval, before producing something totally new.

4. CURRENT RESEARCH ON COGNITIVE ASPECTS OF DESIGN

The previous section presented a study of the contributions that cognitive psychology brings to the study of the design activity. In this section, the results of a survey of journal articles from the last five years are presented—with some major papers from the last ten years—on cognitive aspects in design. The current research is represented in Table 1.

4.1. General scopes of the studies

Some argue that the description of the design process in terms of cognitive processes must serve as a basis for a design theory (Dörner, D., 1999; Christiaans, H. H. C. M. & Dorst, K. H., 1992). Many studies aim as well at improving design process methodologies (Pahl, G. et al., 1999a; 1999b; Fricke, G., 1999; Hacker, W., 1997). The aims of other research studies are towards improvement of the whole design process (Pahl, G. et al., 1999a; 1999b; Condoor, S. S. et al., 1992).

Some authors emphasize the importance of external design support to overcome human cognitive limitations. Sketching is of great importance (Römer, A. et al., 2000; Kavakli, M. & Gero, J. S., 2001; Ullman, D. G., 2002). Römer, A. et al. (2000) suggest prototyping as another good means. Ullman, D. G. (2002) and Shah, J. J. et al. (1994) insist on the need to re-think CAD systems. Ball, L. J. et al. (1998) propose a support system based on artificial intelligence.

Some articles are dedicated to design education (Atman, C. J. et al., 1999, Adams, R. S. & Atman, C. J., 1999).

Some have theoretical implications for cognitive psychology: Goel, V. & Pirolli, P. (1992) detected invariant features in problem solving that are common to the domains within design.

4.2. The design processes concerned

Only a few papers dealt with embodiment and detail design. Most of them study problem solving in a "task-understanding-solution-generating-evaluation" way rather than "analysis-synthesis-evaluation". The problems to solve by the subjects of experiments are on a conceptual level (see Atman, C. J. et al., 1999; Adams, C. J. & Atman, C. J., 1999; Fricke, G., 1999; Hacker, W., 1997; Shah, J. J. et al., 1994; Christiaans, H. H. C. M. & Dorst, K. H., 1992; Pahl, G. et al., 1999 for a description of research studies).

Römer, A. et al. (2000), however, tested students on the benefits of an external support for a design to embody. Fricke, G. (1999) deals partly with embodiment and detail design, but the study focuses mainly on task clarification. There is clearly a lack of studies focusing exclusively on embodiment or detail design.

[2] This article is also a review of research in creativity in cognitive psychology.

Table 1. Survey of studies on cognitive aspects of design

General scopes of the studies	Design theory Design process methodologies Design process as a whole Design supports Design Education Theoretical implications on cognitive psychology
Objects of the studies	Clarification of the task Conceptual design Problem understanding Idea generation Evaluation Design supports Sketching CAD system AI systems Designer's characteristics
Cognitive approaches	Problem solving Problem space Heuristics Thinking process Knowledge-based models Retrieval and use of information Knowledge representation: concepts and categories, schema Imagery Memory Human intelligence Artificial intelligence
Findings for problem solving in the process of design	Confirmation of the validity of prescriptive methods but Claim for an acknowledgement of findings in cognitive psychology: Dealing with early appearance and persistence of a kernel idea Failure to search for alternative solution Design fixation (inclination to stick with early satisficing solutions) Superficial assessment, subjective judgment Hypothesis of inhibitory memory processes subsequent to recognition of familiar solution Lack of flexibility in designer's thinking behavior Claim for design supports, as extensions of the designer Sketching Improving 3D system Intelligent systems for retrieval and reuse
Study Methods	Experiments: Study of the cognitive aspects of individuals during design: Verbal protocol analysis and Sketch analysis Quantitative study

Some papers go beyond the design process. This is the case when the work was not attached to the task. Eisentraut, R. (1999) stated that a designer does not tend to change a problem solving "style" (uses the same methodology) when facing a new problem. Pahl, G. et al. (1999a) reported works on "significance of personal characteristics". Finally, some articles consider the possibility of treating different design sciences as a whole, considering for example the possible commonalities between architectural design, mechanical design, programming and electronic design (Goel, V. & Pirolli, P., 1992, Adams, C. J. & Atman, C. J., 1999, Ball, L. J. et al., 1998, Suwa, M. et al., 1998, Kavakli, M. & Gero, J. S., 2001, 2002).

4.3. Cognitive approaches

The articles have studied problem solving in design process from different points of view: some consider the problem-solving process directly; others study it through knowledge, imagery, memory, or intelligence; still others opt for a hybrid approach.

Fricke, G. (1999) studied the ability of designers to deal with variously precise design problems. Thus special attention is directed towards strategies and heuristics adopted in clarifying the task, generating ideas and evaluating them. Two important parameters are technical knowledge and heuristic competence (ability to plan and control the problem-solving process for new types of problems). Hacker (1997)

reports that emphasis must be put on the problem-solving phases. In Adams, C. J. & Atman, C. J. (1999), a new model of PSP is developed for explaining the transitions between different steps of the problem-solving process: this was explained by transitions between cognitive activities considered as information processing activities and decisions/action activities. Pahl, G. et al. (1999), reporting 12 years of empirical studies in Germany, applied the results to the design process: they are largely based on cognitive activities underlying the problem-solving process. A strong emphasis is also placed on the search through problem space and the strategies or heuristics used by the designer to arrive at a solution. Eisentraut, R. (1999) also studied the general strategies of designers. The notion of problem space has now been widely accepted and is even integrated as a theoretical structure for explication of the general process of designing (e.g. Dym, C. L. & Little, P., 2000, pp. 135–146). A very few, like Dörner, D. (1999), considered the forms of thinking inherent in PSP. Hacker, W. quotes Pahl, G. (1994) regarding the field of intelligence.

Other research studies are connected to knowledge. Condoor, S. S. et al. (1992) urged the acknowledgement of categories and concept models of knowledge. The formation, recognition, and retrieval of concepts and objects are important in design. However, most of the other studies focus rather on retrieval of design actions, using more complex models like the schema (Christiaans, H. H. C. M. & Dorst, K. H., 1992, Ball, L. J., 1998).

Imagery, related to the activity of sketching, attracts the attention of many scientists. That was tackled in the research framework of Pahl, G. et al. (1999); Kavakli, M. & Gero, J. S. (2001,2002) use the mental imagery theory to describe cognitive activities executed while sketching. Suwa, M. et al. (1998) and Römer, A. et al. (2000) also use imagery but focus more on sketching as a means to relieve the load on immediate memory, to retrieve knowledge elements, and to trigger thinking processes. Römer, A. et al. (2000) insist on the importance of external supports, not only sketching but also modeling and prototyping. Ullman, D. G. (2002) stresses only the memory model to show the need of sketching and the need for CAD systems to be adapted to human memory systems, i.e. to permit drafting as fast as sketching.

Finally, some studies concern a combination of cognition domains, like Ball, L. J. et al. (1998), who looked at the problem-solving phases, as well as memory and knowledge. Hacker, W. (1997), listing the contributions of cognitive ergonomics, invokes PSP, imagery and memory.

4.4. Findings

Concerning the design process, Atman, C. J. et al. (1999) and Adams, C. J. & Atman, C. J. (1999) confirm the validity of prescriptive methods in the design process. The students who considered more alternatives had a better result quality. Other studies, however, temper these findings. Designers observing the prescribed methodologies will be on average more successful than those who do not (Pahl, G. et al., 1999), but prescriptive models “are in conflict with natural cognitive models” as Condoor, S. S. et al. (1992, p. 277) claim. These authors list human behaviors and characteristics that contradict rigid procedures: Early appearance and persistence of a core idea; Lack of generation of alternatives; Design fixation; Lack of flexibility; Subjective judgment; Reluctance to change after a design is made; “satisficing”. Ball, L. J. et al. (1998, p. 213) complete the picture: failure to search for alternative solutions, marked inclination to stick with early “satisficing” solutions, only superficial modeling and assessment of competing alternatives when such options are actually considered. The claim is that these “human specificities” should be integrated in methodologies. Fricke, G. (1999) noticed that good designers did not suppress their first solution ideas, but did not exploit them until the clarification of the task was complete. His conclusion is that this should be practiced in teaching.

Simon, H. A. (1996, p. 119) defined the term “satisficing” to refer to procedures that search “good or satisfactory solutions instead of optimal ones”. This concept explains why a designer can stop searching, having only the “feeling” that he has reached a sufficient solution or set of solutions (Pahl, G. et al., 1999a, p. 484). Sometimes, solution search stops even without a satisficing one; another phenomenon may be behind this. Ball, L. J. (1998) uses the hypothesis that an inhibitory memory process can arise subsequent to the recognition-based emergence of a familiar design solution. Pahl, G. et al. (1999a) report that research showed that various approaches lead to good solutions; that sub-problem-oriented (opportunistic) procedures are also successful depending on the problem; that methodology is useful but never rigorously followed, and that there is a need for more flexibility in methodology, but not in an individual and situation-oriented manner. Eisentraut, R. (1999)

confirms this view. The way humans solve problems is not really flexible, whatever the problem may be.

The general conclusion from these findings is that 'biases' introduced by human cognition have to be taught, so that the students will be aware of them, and that procedures should be employed less rigorously.

The next point concerns the external supports to help embody artifacts. Ullman, D. G. (2002) emphasizes sketches to relieve strain on the working memory, and improvement of CAD systems to adapt to a designer's speed of thinking. Römer, A. et al. (2000) strengthen the case for psychological research: sketching gives supportive aid for memory as well as for thinking. Suwa, M. et al. (1998)'s experiments, like Römer, A.'s, show that sketches serve as an external memory, as a cue for association of ideas, and "as a physical setting on which thoughts are constructed". Ball, L. J. et al. (1998) propose an interface agent from AI linked to a knowledge management tool for generation and evaluation of concepts. This agent focuses not only on solution findings but on design process re-use as well.

Davies, S. P., (1995) however, poses a strong restriction concerning support design systems based on active (manual or verbal) expressions of the design process. Indeed, the designers have to describe their own design process to feed and activate such systems, which can in turn retrieve former designs. But, having to describe the design activity is not a part of this activity itself. The description given by participants in a study based on verbalization can introduce a bias. Moreover, that "may impose a structure upon that process which would otherwise be absent." (1995, p. 113). This partly explains problems encountered by such a design support system (Lambell, N. J. et al., 2000, pp. 452-453).

The differences between novices, intermediates, and experts are significant. The participants in the experiments are generally classified as follows: novices or freshmen (they had just begun learning design), intermediates or "senior" students (last-year students or just graduated), and experts (from 3 to 25 years' experience). Atman, C. J. et al. (1999) recorded better quality from the last-year students. Christiaans, H. H. C. M. & Dorst, K. H. (1992) report as well that 2nd-year students were not asking any questions, accepting the given specifications as sufficient; more experienced designers gathered more information. Concerning design procedures, experts tend to do more transition between design steps (Adams, C. J. & Atman, C. J., 1999; Atman, C. J. et al., 1999; Christiaans, H. H. C. M. & Dorst, K. H., 1992; Pahl, G. et al., 1999). It has been noticed that experts, with better knowledge, even tended to operate opportunistic strategies, i.e. could follow sub-problem-oriented procedures with success instead of applying a systematic approach at all design steps. Others, like Davies (1995), object that an expert's behavior is broadly top-down with local opportunistic episodes. Fricke, G. (1999) found that good designers have a balanced approach. According to Ball, L. J. (1997), a designer only uses an opportunistic strategy when faced with "difficulties, uncertainty, and design impasses".

The expert, however, has no special capacities. It has been shown that the domain-specific knowledge (developed schemata) makes the expert, and not unusual abilities (Christiaans, H. H. C. M. & Dorst, K. H., 1992). Experts cannot be differentiated in terms of intelligence determined by classical tests (Pahl, G., 1994 quoted by Hacker, W., 1997, p. 1089). Other studies showed that ideas are found by retrieval rather than by creativity (Pahl, G., 1999). Furthermore, studying sketches (Kavakli, M. & Gero, J. S., 2001; 2002), it has been observed that cognitive activities of the novice dropped at some moment, which signifies unfocused attention. Moreover, the expert's cognitive activity while sketching can be modeled as tree-structured, while the novice has more categories of activity that are difficult to relate to each other. More structured design strategies and focus could be the reason why experts have high performance. But Kavakli, M. & Gero, J. S. raise the following question: could unfocused attention and poorly structured activity lead to more novelty? Unfocused attention might make remote idea associations more accessible (like the incubation step in the creativity process); ambiguity in sketches can play a similar role.

Knowing the expert's reasoning, knowledge structure and retrieval is a "must study" for development of expert systems and improvement of education.

Finally, concerning education, Pahl, G. et al. (1999), Fricke, G. (1999), Condoor, S. S. et al. (1992) argue for an acknowledgment of, and teaching, the limited human capacity to follow rigid procedures. The work of Adams, C. J. & Atman, C. J. (1999) is oriented towards the teaching of design. Research on teaching design based on cognitive aspects is in fact just in its infancy.

4.5. Methods used

The papers reviewed remarkably used slightly different kinds of methods, which can be gathered under the heading of Verbal Protocol Analysis (VPA) and sketch analysis, inspired by cognitive psychology methods.

Basically described in Ericsson, K. A. & Simon, H. A. (1993), VPA consists of asking the participants "to think aloud" during a design process, and then studying their descriptions. However, the protocols include not only recorded documents, but sketches and notes of the designer as well. The participants are sometimes recorded on video and afterwards transcribed (Fricke, G., 1999). Christiaans, H. H. C. M. & Dorst, K. H. (1992) give students a preliminary exercise for training. Then a scheme for coding designers' cognitive actions, based on a preliminary analysis of protocol content (Ball, L. J. et al., 1998), is created (as in Suwa, M. et al., 1998; Gero, J. S. & McNeill, T., 1998) or modified (Kavakli, M. & Gero, J. S., 2001; 2002), depending on the scope of the study. The categories of the coding schemes and the segmentations of the protocol are up by the authors, but once the instantiations have been realized, a statistical treatment of the results can be made.

Dorst, K. H. & Dijkhuis, J. (1995) discussed two paradigms for describing design activity. The process-oriented approach focuses on the relations between the designers and the design process; the categories of the coding schemes are in terms of design stages, information processed, and the artifact (e.g. Purcell, T. et al., 1996; Atman, C. J. et al., 1999). Most of the methods employed by the articles reviewed belong to "design as a process of reflection-in-action" (1995, p. 262). The aim is to be closer to the designer's cognitive activities in order to observe, for example, the influence of knowledge or memory on the design actions, as in Suwa, M. et al. (1998) or Kavakli, M. & Gero, J. S. (2001; 2002). Dorst, K. H. & Dijkhuis, J. (1995) suggest that problem-solving processes where the initial and final states, as well as the strategy, are relatively clearcan be studied with the first approach. This can be enhanced for some of the scopes of study of embodiment and detail design (how are the designers using the basic rules, guidelines and principles, for example), while the others have to be approached by closer studies of the cognitive activities.

Davies, S. P. (1995) warns against a study solely based on verbalization. His study reveals strong indications that verbal descriptions may not map well onto behavior, and even that describing the design activity may affect the process itself. The hypotheses that can explain this fact are first that VPA was originally used for well-defined problems. There is a need to show that this method is accurate for more complex studies. The designer will naturally tend to avoid saying that he or she is acting irrationally, if this is the case, giving a rational justification post hoc. The act of verbalization can change the focus; language itself can impose its own structure. This study suggests that VPA should be coupled with visual protocols by means of video recording. In a prior publication, Shah, J. J. et al. (1994, p. 213) had already identified such criticisms, and developed a non-intrusive method, with two designers working co-operatively, which would "provide a 'natural' setting for articulating what is going on in their (subjects) minds". But even so, some problems remain (e.g. do the designers describe all their thinking processes?), and comparison studies as in Davies, S. P. (1995) remain to be carried out.

5. DISCUSSION

The aim of this section is to reflect on the research area and discuss future directions that can be explored.

5.1. Embodiment and detail design

Most of the literature refers implicitly to the cognitive aspects of the design activity of the conceptual design phase. This may be due to the fact that, at a conceptual level, the problems given to the designers are ill-defined and potentially cause great biases in the research on the solutions. Moreover, conceptual design is characterized by a strong demand on creativity and the attempt to understand it. The stakes of this phase are high for the further development of a product. Finally, some studies hypothesize that the designer is subject to the same human-dependent 'biases' during any design activity, whatever the design process phase.

However, this assumption needs to be examined. Some findings may not be compatible with, or not answer to, the specificities of embodiment design and detail design. It was previously mentioned that the problem-solving process is rather of the type "analysis-synthesis-evaluation" than "task-understanding-solution-generation-evaluation". Moreover, embodiment design is based on basic rules: *simplicity*, *clarity* and *safety* (see e.g. Pahl, G. & Beitz, W.,

1997/1996; Sundström, J. et al., 2000). These basic rules are supported by *guidelines* based on the constraints of the design, defined during conceptual design. They cover the range of "design for X" as well as ways of dealing with some physical and natural effects like corrosion, wear and thermal expansions. Finally, rules and guidelines are complemented by *principles*, kinds of 'laws' that have been verified by practice and that facilitate the design (Matousek, R., 1963; Leyer, A., 1964; French, M. J., 1998; Pahl, G. & Beitz, W. 1977/1996).

These specificities — basic rules, guidelines and principles —— certainly have an impact on the problem-solving process used by the designer. These rules can be questioned: when and how does the expert design with simplicity or clarity? How to characterize them? Does he seek some support from the guidelines and have in mind the principles during effective embodying and detailing? Is there any human limitation to their application? What tool can be offered to support the embodying and detailing design processes? How are the differences between novices and experts expressed? What characterizes an expert in embodiment and detail design?

Teaching embodiment and detail design is also involved, thus touching on the structure of domain-specific knowledge. Questions can be asked about the efficiency of the "right-or-wrong" examples to provide the most adequate basis for learning (already mentioned in Matousek, R. 1963). Likewise, are the empirically based guidelines (simplicity, clarity, safety) satisfactory for the students?

5.2. Implementation of the findings

Improvement of the design process

Among the discoveries made while studying the cognitive aspects of the design activity, only very few are currently used beyond this research area. The concept of problem space is one such discovery: it serves when modeling the designer's solution path (as well as in artificial intelligence). Nevertheless, the cognitive constraints that limit the designer's ability to solve problems, the concepts of "bounded rationality" or "satisficing", are still absent from most of the classical design process methodologies.

Computer-based implementations

The exploitation of the findings by computer-based systems is slowed down by difficult challenges. Lambell, N. J. et al. (2000) reported the shortcomings they encountered during the implementation of an expert system: An external support system reduces the pace of the thinking process; The designer feels "directed" — what gives him or her the (false?) impression of decreasing his or her creative capacity? Even the visual aspect of the software played a role. The implementation of the findings about the designer's cognitive abilities is irreversibly linked to research in computer-human interactions.

5.3. Validity of the experiments

The debate about whether design is a science like physics or not has always been alive. In this particular area, the hypothesis is that the observed phenomena (the cognitive processes during the design activity) are common or accessible to every human being, i.e. under some assumptions, "natural" and "repeatable", thus ensuring the validity of the experiment — in an epistemological perspective. The global scientific approach is thus similar to classical physics: observations of a phenomenon, elaboration of a falsifiable theory, reduction and repetition of the phenomenon in the frame of an experiment, verification of the finding "in real life". This use of a hypotetico-deductive methodology is also the traditional research process in cognitive psychology (Ball, L. J. & Ormerod, T. C., 2000a). Let us take the case of this phenomenon: "early appearance of a core idea". It was brought to light in the seminal work of Darke (1979) by the means of interviews. This has been taken up again by Condoor, S. S. et al. (1992) and Lawson, B. (1997, p. 44-45), and used in Atman, C. J. et al. (1999) to build work hypotheses, and tested in Ball, L. J. et al. (1998), among others. It was finally a part of the support system tested by Lambell, N. J. et al. (2000).

Aside from the epistemological perspective, some questions remain concerning the validity of the experiment.

Reliability (to what extent the study can be repeated) is important for the repetition of the experiment. Most of the papers reviewed gave the number of participants, and the design in brief, but only few revealed the experimental conditions.

Internal validity (to what extent the results reflect reality) is a point of controversy. The "instruments" that transform the verbal protocol into problem-solving process diagram are the researchers responsible for the experiment. Methods have been worked out to thwart the bias. The usual way of analyzing is that two researchers do the job separately and compare their results (e.g. Atman, C. J. et al., 1999). Pur-

cell, T. et al. (1996) propose a four-stage analysis: the two coders apply the coding scheme twice, compare the results, then compare each other's results and finally work together for a final arbitration between the results. Recently, Shah, J. J. et al. (2003) have been developing a system of comparison between the analyses of researchers in design engineering and psychologists. Engineers analyzed designs of high complexity while psychologists analyzed "simpler" ones. The purpose of the study: ideation, remaining the same (the experiment is based on sketch analysis). It turned out that they matched. This has the advantage of decreasing the time of analysis, and this confirms the internal validity of the experiment.

External validity concerns the extent to which the results can be generalized. This subject has not been tackled very often. Only a few studies were found that sought some similarities between the different engineering fields (Goel, V. & Pirolli, P., 1992; Lloyd, P. & Scott, P., 1994). Surprisingly, very few studies discuss the problem of the number of experiments that would give external validity to the study. Indeed the number of subjects studied varies from 1 to 52 experiments from paper to paper. The comparison between the experiments of different laboratories is difficult due to the "scattered and independent nature" of the studies (Cross, N. et al., 1996b). Cross, N. et al. (1996a) developed a workshop where researchers from different universities worked on the same experiments, which allowed better bases for comparison. The reason for the small number of experiments seems to be the fact that the works are still explorative in nature (see e.g. Ball, L. J., 1998), and that analysis is a very time-consuming task. Some sociologists give a justification for a small number of studies: Eisenhardt, K. M. (1989) writes about case-based studies that they are chosen for theoretical, not statistical reasons. Then, if the choice of the sample is correctly made (polar cases like experts and novices are really interesting for this purpose), the results should be valid. However, this justification needs a preliminary acceptance of the paradigm it belongs to (here: postpositivism). This subject needs further exploration.

5.4. Placing the findings in context

The experiments on the design activity are studies of a phenomenon that has been isolated from other parameters, among others sociological ones, in order to better understand it. The survey revealed that observation studies and verification of the phenomenon are proportionally fewer than the experiments. This can be due to the fact that this field of study is still in its infancy. Nevertheless, if the cognitive characteristics of the design process have to be exploited, they have to be placed in their context, and confronted with the other phenomena influencing the design activity, especially social factors. Their interrelations might be complex.

Ethnography is one of the methods: "it problematicizes the ways that individuals and groups constitute and interpret organization and society on a daily interactional basis" (Schwartzman, H. B., 1993). Ball, L. J. & Ormerod, T. C. (2000b), for example, adapted it and used it — focusing on designers' interactions with their environment, and no longer exclusively on their cognitive activities prior to the study itself, to learn how the design process takes place.

5.5. Extension: origins of knowledge

Research studies have given many insights into how experts design, which are their strengths. They have been compared to students, and more and more studies are deciphering the differences (e.g. Kavakli, M. & Gero, J. S., 2001; 2002). Teaching the way experts design: this goal is really important for education. However, analyses of cognitive processes yield information on how the designer works, but not on how he acquired these skills. Thus, complementary to these analyses, retrospective interviews may be needed to get to know where the solutions came from and in what proportions: education, experience, earlier designs, etc. In this way, the experts' skills could be better encircled, and then taught to novices. Finally, designers' reflections on their task could teach us more about the strategic and tactical level of a design activity than VPA does.

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