Modeling cognitive and affective processes of designers in the early stages of design: mental categorization of information processing

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Modeling cognitive and affective processes of designers in the early stages of design:

Mental categorization of information processing

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T H È S E

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LIST OF ABBREVIATION

CAD	Computer-aided design
EXP	Experiment
ER	Early representation
GSR	Galvanic conductance response
HCI	Human Computer Interaction
HYP	Hypothesis
IR	Intermediate representation
LTM	Long-term memory
PCA	Principal Component Analysis
SCR	Skin Conductance Response
STM	Short-term memory
SM	Sensory memory

GENERAL INTRODUCTION

AIMS AND OBJECTIVES

This study aims to explore how designers mentally categorize design information during early sketching activities performed in the generative phase. The generative phase is characterized by the production of sketches to find a ‘‘good form’’ of one or several concept(s). In order to achieve this, it should be noted that cognitive and affective processes of designers, involved in this specific phase, should be formalized through understanding designer’s mental process and its relationship with early representations (sketches) together.

The objectives of the study are:

- to study what kind of mental information is extracted and how it can be transformed or categorized through cognitive operations during early sketching;
- to explore the affective processes of designers that would interplay with their cognitive processes in generating stimuli and evaluating their results during the mental categorization of information processing;
- to identify emotional response to early representations (sketches);
- to quantify this emotional response by combining cognitive and physiological methods;
- to provide system specifications for developing a computational tool dedicated to the generative phase.

RESEARCH QUESTION OF THE STUDY

Given that early stages of design are considered to be among the most cognitively intensive in the design process, several studies have been investigating these stages in order to progressively formalize and develop a model of these. However, since much design research focuses on the external information and the explicit design process, there has been a research gap between the informative and earliest generative phases, which are relatively implicit. We defined this specific gap as a phase of ‘mental categorization of information processing’ in this thesis. During this phase, designers employ various levels of mental information, and gradually integrate and synthesize them into their memory in order to generate early sketches. Thus, it is necessary to develop a cognitive model dedicated to this specific phase wherein designers mentally categorize design information. In addition, along with a growing interest in hedonic aspects of product design, emotional aspects of design activity should be taken into account in conjunction with their cognitive aspects. Given that our interest focuses on the earliest generative phases, the emotional response to early representations are of great interest. It allows us to understand how designers put the emotions to their early representations and how early representations themselves can convey an emotional dimension.

Therefore, we raised the research question about **how the cognitive and affective processes of designers can be modeled, specifically, during mental categorization of information processing performed in the generative phase.**

CONTRIBUTION OF THE STUDY

The key contributions of the study in the perspectives of both scientific and industrial communities can be summarized as follows:

- **A model of cognitive and affective processes of designers, dedicated to mental categorization of information processing in the generative phase**

We developed a model of cognitive and affective processes of designers, where they mentally categorize design information to generate early sketches (chapter V). This model consists of two cycles that represent the mental categorization of information and early sketching in the generative phase. First, a model of mental categorization of information processing was focused specifically on the structure of design information (high, middle, and low-levels) and cognitive operations (association and transformation), which provide clues to identify how mental information is encoded and stored in long-term memory (LTM) and moved to working/short-term memory (WM/STM). This model was then extended to 'early sketching in the generative phase', because early sketches can be used as an external memory and interact with internal memory of designers. In addition, along with the cognitive processes of designers, we illustrated how emotional reaction of designers may control this specific phase in generating stimuli and evaluating their results.

- **Specifications for computational tools dedicated to the generative phase**

Given that the notion of information level was initially derived from the field of artificial intelligence, where it is used to develop specific algorithms, we developed a list of specifications for the development of computational tools, specifically dedicated to the generative phase. This involves the construction of databases (semantic descriptors, archetypes, divers analogy issues from different sector), and an association between design information, transformation of forms (morphing in terms of semantic descriptors, or analogy), also a support of the memorising process of design precedent, and so on. The detailed system specifications will be listed in section 5.3.

ORIGINALITY OF THE STUDY

Original research advancements were provided in several areas: an emerging topic of research ‘’mental categorization of information processing in the generative phase’’, an interaction between cognitive and affective processes in design, applying both an action research and laboratory-based experiments, the prediction of emotions from early representations (sketches), and the integration of theories and methods from psycho-physiology in design research.

- **Exploring an emerging topic of research: the mental categorization of information processing in the generative phase**

  We bridged a research gap related to mental processes and early representations between the informative and generative phases. This specific gap was defined as ‘’mental categorization of information processing in the generative phase’’ in this thesis. Both theoretical and empirical studies with product designers enabled us to explore how designers mentally categorize design information during early sketching.

- **Considering the interaction between cognitive and affective processes in design research**

  The interplay of cognition and emotion is an emerging subject. Even though many cognitive psychology and design researchers have pointed out possible emotional impact during cognitive processes from a theoretical point of view, no empirical studies have been conducted to date in design. In this thesis, based on empirical studies of the activity of product designers, we partly validated that emotional reactions of designers may interplay with their cognitive processes in generating stimuli and evaluating the outcomes during the generative phase.

- **Applying both an action research and laboratory-based experiments**

  A combination of action research and laboratory-based experiments was particularly appropriate for our study. Thus, first, a descriptive model of information processing involving memory theories drawn from cognitive psychology was developed. This model was refined and enriched via two experiments (EXP 1 and EXP 2) with twenty eight product designers (experts and novice). Subsequent analysis yielded a cognitive model depicting the mental categorisation of design information processing performed by designers. As an application, based on our model, a list of specifications for developing computational tools dedicated to the generative phase has been applied and validated in the ‘’GENIUS’’ project.

- **Exploring the prediction of emotions from early representations (sketches)**

In the generative phase, designers already have own mental information. Their early sketches are the first externalization of this mental information. Therefore, the prediction of emotions from early representations was important to meet designer's intent (semantic and emotional) and emotional responses of consumers from the early stages of design. Based on our experiment, we confirmed that early sketches are able to express semantic features, and ''good form'' of early sketches may elicit positive feelings and high arousal state.

- **Applying theories and methods from psycho-physiology**

It was an interesting trial to integrate methods and theories from two disciplines – design science and cognitive psychology – to formalize implicit information process, specifically in the designers' activities. Moreover, given that early sketches might be hard to elicit emotions rather than other images having multidimensional attributes, we combined cognitive and physiological methods to quantify the emotional response to early sketches. This combination enables to objectively measure a subtle emotional state and specify it with secondary emotional terms. In addition, the comparison between different ways of measuring emotions in these specific stimuli (early sketches) will also be of great interest for the discipline of psychology.

STRUCTURE OF THE DOCUMENT

Chapter I Context

Chapter I introduces the major topic of our thesis, and explains its industrial and academic context. Design research is strongly related to theoretical and practical challenges to understand current trends and new needs in the industry and research. Three issues related to industrial context are identified: social, economic & political, and technological issues (§1.1). The academic context starts with a historical survey on two paradigms of design science: between 1920s-1960s and later 1960s. Then, it explains how design research became a major interdisciplinary theme mixing design cognition and emotion (§1.2).

Chapter II State of the art

Chapter II provides the state of the art of cognitive and emotional aspects of design as well as the review of cognitive and physiological methods based on relevant design science and psycho-physiology literature. This chapter is divided into three sections. The first section focuses on the designer's cognitive activity in the early stages of design (§2.1). The second section brings together the previous design studies relating to cognitive and emotional aspects in design, and aims to understand their interplay (§2.2). A review of methods to measure designer's activity from cognitive to physiological methods is provided in third section (§2.3). Finally, chapter II is concluded by synthesizing the findings from scientific literature and delimiting the research problems. It finally leads to the formulation of research questions and the development of hypotheses in chapter III.

Chapter III Research question and hypotheses

Chapter III formulates a research question and develops the hypotheses of this thesis. The core research question explored in this thesis is related to **how the cognitive and affective processes of designers can be modeled, specifically, during the mental categorization of information processing performed in the generative phase**. Two main hypotheses are explored: **Hypothesis 1** suggests developing a model of the cognitive and affective processes, whereby designers mentally categorize design information; **Hypothesis 2** proposes that emotional reactions to early representations (sketches) should be formalized in order to predict their emotional dimensions.

Chapter IV Empirical study

In chapter IV, two experiments were designed to test the specific hypotheses developed in Chapter III. EXP 1 aims to formalize how designers mentally categorize design information during early sketching performed in the generative phase. We conducted a protocol study with sixteen product designers based on a descriptive memory model derived from cognitive psychology. Our experimental field was the GENIUS project, which aims to develop the software tool for supporting designer's activities in the early phases of design process (§4.1).

The aim of EXP 2 is to identify emotional reaction to early representations (sketches). It also introduces how the cognitive and physiological methods can be combined and applied in this study to quantify the emotional response to early sketches (§4.2). Each sub-section includes results and discussion. Finally, it concludes on the validation of our hypotheses.

Chapter V Modeling cognitive and affective processes of designers in the generative phase

Chapter V presents our key contributions based on the results from the empirical studies conducted in chapter IV. The first two sections propose a specific model depicting the mental categorization of information processing performed by designers in the generative phase (§5.1 and §5.2). The third section suggests a list of specifications for developing a computational tool dedicated to the generative phase (§5.3). Finally, this chapter concludes by summarizing our contributions in the perspectives of both scientific and industrial communities (§5.4).

Chapter VI Conclusions and perspectives

Chapter VI follows general conclusions by recapitulating the thesis (§6.1); and then it closes by discussing directions for further studies aiming at (§6.2):

- refining various aspects of design process, being cognitive, behavioral, and affective;
- increasing emotional dimension from early representations to final products; and
- formalizing early stage of design process with computational support tools.

I. CONTEXT

Introduction

This chapter introduces the major topic of this thesis and explains its industrial and academic context. Design research is strongly related to theoretical and practical challenges to understand current trends and new needs in the industry and research.

The first section addresses the industrial context. Three issues related to industrial context are identified: social, economic & political, and technological issues. The major interesting movement is summarized in each issue.

The second section brings the academic context. It starts with a historic survey on two paradigms of design science: from the 1920s to the 1960s and since the 1960s. Then, it explains how design research became a major interdisciplinary theme mixing design cognition and emotion.

Finally, the third section introduces some leading research groups on the subject of design cognition and emotion in France and abroad.

1.1 Industrial Context

1.1.1 Social issues: the role of design and designers in a creative society

Since American Sociologist, Daniel Bell, firstly introduced the notion of "information society" in 1973, many people increasingly have talked about the transition era from the "Industrial Society" to the "Information Society" during the late 1980s. While "Industrial revolution" was initiated by the emergence of manufacturing technology with a development in transportation, "Information society" resided in the development of Information and Communication Technologies (ICTs), and the World Wide Web (WWW) **(Burch, 2005)**. During the late 1990s, the notion of "information" has been rapidly transformed into the "knowledge", which strengthened a concept of generation, sharing, and globalization. This movement led to the economic shift from industrial manufacturing to knowledge work and service delivery. Innovation terrain has been thus expanding **(Brown, 2008)**.

From the early 2000s, people began to talk about "Creative society", beyond "Knowledge society". Creative society is based on our ability to think and act creatively, rather than what we know or how much we know previously **(Resnick, 2007)** (See Figure 1).

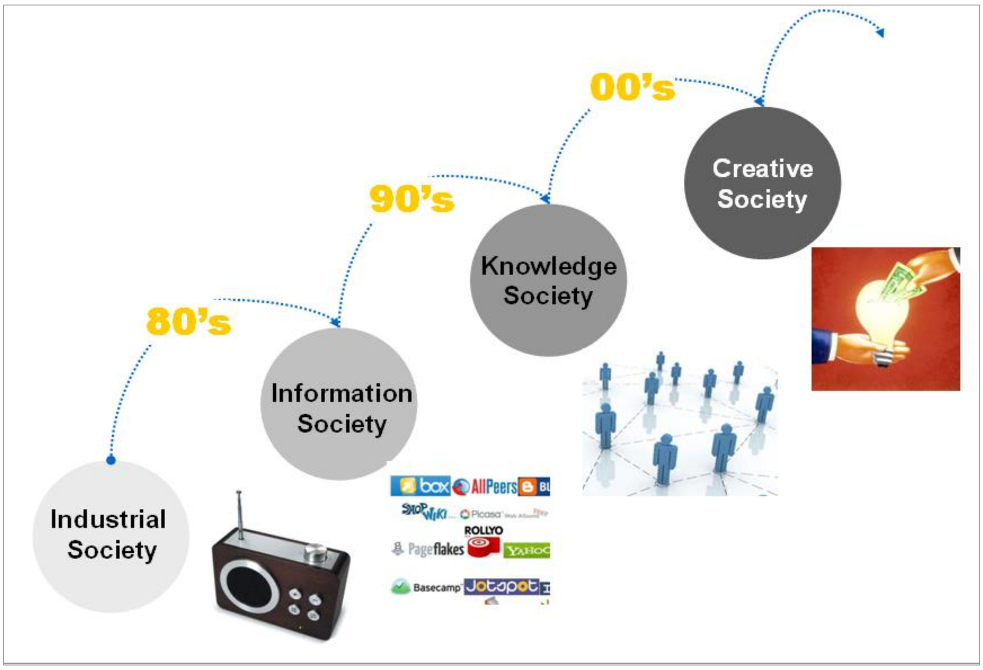


Figure 1. Changing society toward the creative society

The evolution of a society also leads a changing role and notion of design. As shown in Figure 2, the developments in science and technology dating to the industrial revolution have been of great research interest; however, historical accounts have paid comparatively little attention to the role of consumers (users) and designers. Since the widespread introduction of the notion of "user-centered design" during the late 1990s, the research on consumers in the service of enhancing interface design, improving usability, and so on has become common. Nowadays, during the transition from a knowledge society to a creative society, the research into the role of designers has been growing and leading to a substantial increase in the value assigned to certain domains **(Cox, 2005; Resnick, 2007; Brown, 2008)**.

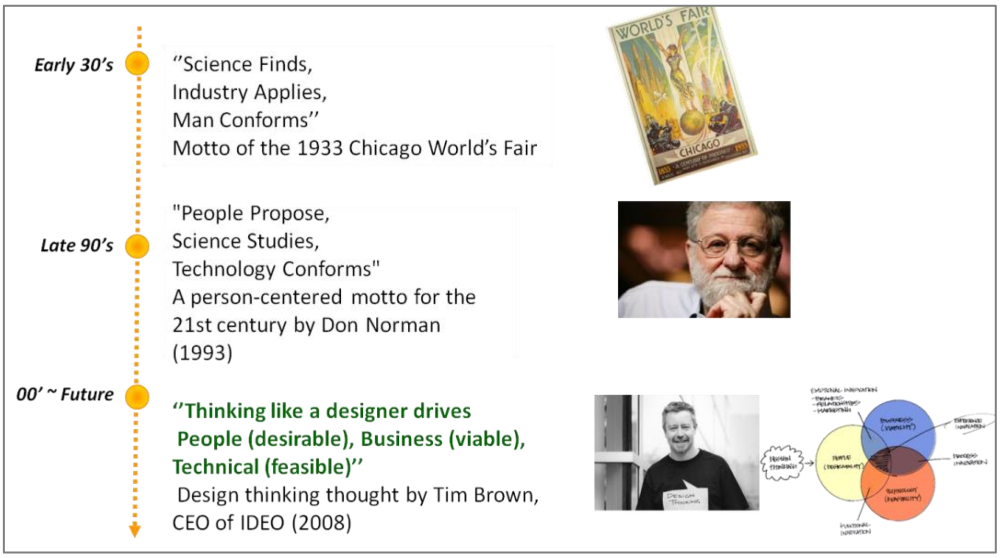


Figure 2. Evolution of the role of designer

From the viewpoint of 'creativity', the role of the designer is not limited to aesthetics and the 'looks' of product in the later stage of design process **(EU report, 2009)**. Design is more characterized in the following manner: first (1) putting user needs, aspirations, and abilities at the first point **(EU report, 2009)**, and (2) generating new ideas that better meet consumer's needs and desires **(Brown, 2008)**, then (3) shaping ideas to become practical and attractive propositions for users or customers **(Cox, 2005)**.

1.2.2 Economic and political issues: design-led innovation & competitiveness

In the 'Creativity society', the success factor in business – regardless of sector – increasingly depends on the ability for innovation to exploit new ideas and opportunities ahead of the competition. From the micro-economic view, taking the case of UK in Europe, for example, the top innovating companies produce 75% of revenue from products or services that did not exist 5 years ago in UK **(Cox, 2005)**. In addition, according to a recent survey of Business Enterprise and Regulatory Reform **(BERR, 2008)**, 55% of UK manufacturing firms consider design and development as one of the most important sources that could be the competitive advantages in five year's time.

In case of USA, a survey of 2,700 executives done by The Boston Consulting Group **(BCG, 2009)** shows that 45% of executives ranked 'moving quickly from idea generation to initial sales' in below average or pool among the innovation capabilities (See Figure 3). Note that this weakness was identified as the top challenges since 2007 and 2008 surveys, and ranked the poorest in earlier surveys as well, companies need to improve the early stages of design, also called 'idea generation', in order to lead innovation. However, the study on the early stages of design has not been sufficiently integrated in the innovation process. Therefore, design-driven innovation, including design process, tools and methodologies developed and used by designers, need to be considered as an important asset to lead innovation and to develop the competitive power of enterprise. Design-driven innovation is thus a new form of innovation compared to a traditional science or technology driven model.

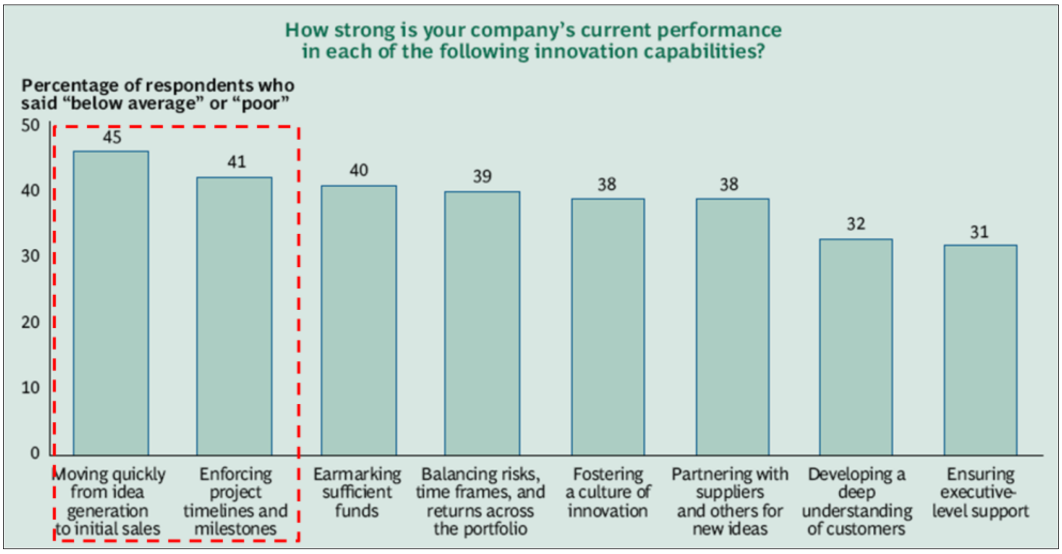


Figure 3. Speed is the companies' greatest challenges (BCG, 2009)

From the macro-economic view, European Commission report **(EU report, 2009)** on ''Design as a driver of user-centered innovation'' compares the national competitiveness of leading countries against their design ranking. The fact prompts that there is a positive correlation between the level of design research and national competitiveness. Figure 4 shows that some countries investigated increasingly design policy (Finland, Denmark, South Korea, France, Italy Germany, UK, and USA) have placed in both high design competitiveness and national competitiveness. This fact yields that national levels of design policies and programmes could influence an important index to lead innovation **(EU report, 2009)**.

Figure 4. National Competitiveness and Design Competitiveness Ranking
(Word Economic Forum, the Global Competitiveness Report 2006/2008, Global Design Watch 2008)

1.1.3 Technological issues: ICT developing tools

In the ''Creative Society'', the new technology and Information Technology (IT) could play a dual role **(Resnick, 2007)**: quickening the pace of change and/or better developing people as creative thinkers. In design practice, this growing trend has been emerging toward the use of computational and Internet-centered tools in the design process as well as the working environment. Designers tend to build their digital databases of design, and increasingly recognize the importance of computational tools within their activities **(Restrepo, 2004; Büsher et al., 2004; Stapper & Sanders, 2005)**. It is partly due to the certain pressure to shorten the development durations and increase in variability of the offer expected by the designers. Those needs lead to formalization and digitization of the early stages of design **(Bouchard et al., 2008).**

However, as shown in Figure 5, for the past thirty years, the development of computational tools for designers have been limited to prototyping technology, such as Computer-Aided Manufacturing (CAM) from UGS Corp. and Dassault System, etc., Computer-Aided Design (CAD), including Photoshop, Illustrator, Solidworks, 3D Max, etc., and Computer-Aided Styling (CAS) to help 2D or 3D drawing, specifically in the automotive sector.

While computational tools tend to focus on detailed design phases, the tools dedicated to the early stages of design have not yet come to the fore. Some pioneers have developed the software tool to support the early stages of design, specifically for retrieving or categorizing inspirational sources used by designers. They include EVIDII and IAM-eMMa **(Nakakoji, 1999)**, Product World **(Pasman & Stapper, 2001)**, CABINET **(Keller, 2005)**, I-VIDI **(Jung et al., 2007),** and recently TRENDS software which was developed in our laboratory (LCPI) as a result of an European project **(TRENDS Website, 2008)**. Those software tools are still limited to exploratory works, not being commercialized.

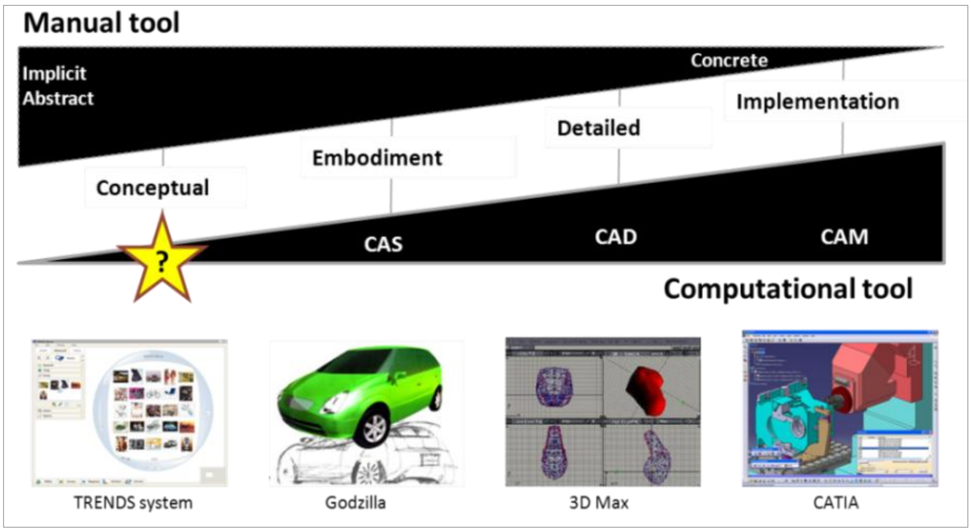


Figure 5. Evolution of the computational support (Kim et al., 2009a)

1.2 Academic Context

1.2.1 History of design science

The modern history of design science is often understood through two important paradigms: from the 1920s to the 1960s and since the 1960s. In the 1920s, design sought a desire to ''scientise'' design, while design pursued a scientific design method and processes in design since the 1960s **(Cross, 2007; Bayazit, 2010)**. From 2000', design science oriented to an interdisciplinary topic, including cognitive psychology, sociology, computer science, etc.

1.2.1.1 First paradigm from the 1920s to the 1960s

Since the ''scientise'' design movement emerged in the early 1920s, design has looked for a scientific design product in combining the art with science and technology, etc. **(Cross, 2007)**. Figure 6 shows a design research chronology into two fields: methodologies and science/industry **(Bayazit, 2010)**. The most important emergence in the ''scientise'' design was the foundation of 'Bauhaus' in Germany. The 'Bauhaus' is the first modern design school; they established design, curriculum including study of construction and representation; materials and tools; color and composition, etc. However, due to the pressure from the Nazi regime, Bauhaus closed in 1933. After 4 years, most faculty of Bauhaus moves to the United States, Britain, or Russia. In 1937, László Moholy-Nagy founded 'NewBauhaus' in United States. That became the foundation of Institute of Design (ID) at Illinois Institute of Technology at the Illinois institute. In summary, the period from the 1920s to the 1960s was a period of emergence of understanding design as a scientific, objective, rational activity.

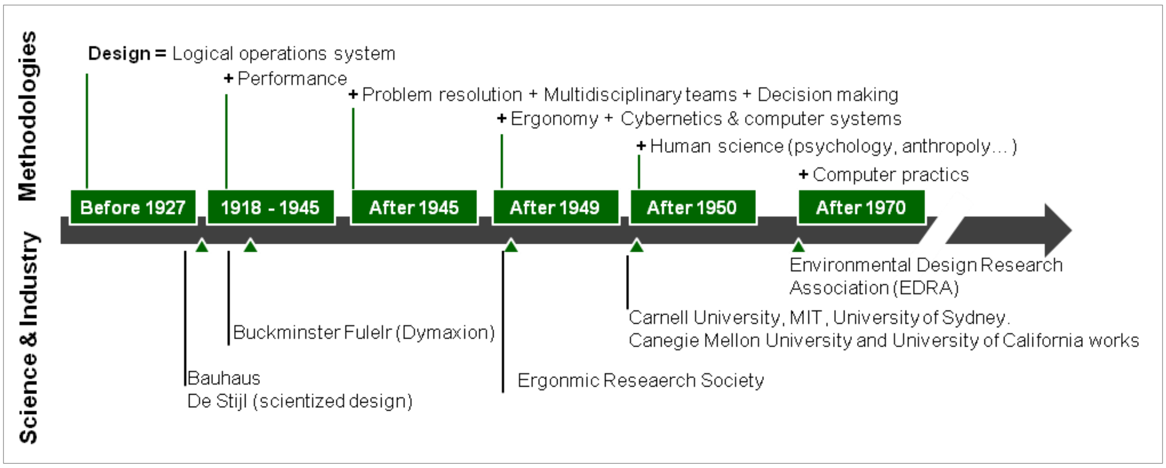


Figure 6. Design Research Chronology (Bayazit, 2010)

1.2.1.2 Second paradigm since the 1960s

While the 1920s looks for scientific design products, since the 1960s, design research was more concerned about method and process. Many researchers published the history of design research focusing on the 1960s, including those of **Cross (1993, 2007), Hubka & Eder (1996), Bayazit (2010)**. ''Design Science'' refers to an explicitly organized, rational, and wholly systematic approach to design; not just the utilization of scientific knowledge of artifacts, but design in some sense a scientific activity itself **(Cross, 2007)**. According to the definition of **Archer (1981)**, "Design research is a systematic inquiry whose goal is knowledge of, or in, the embodiment of configuration, composition, structure, purpose, value, and meaning in man-made things and systems''**(Archer, 1981, p.30-47)**

As pointed out above, accumulation and use of design knowledge is a core activity in design science. In Figure 7, **Owen (1998)** illustrated the dual nature of actions: the processes of using and building knowledge model in context of product design. Knowledge is used to work in design practice, and knowledge from practice is evaluated to build knowledge. Those two ways of understanding design activity is also called as action research approach. According to **Liu (1997)**, an action research approach is a form of reflexive process in encompassing both theoretical and practical concerns while contributing to a scientific method or a model. This approach is of benefit to understand the problem, but also to promote change in design practice **(Reason & Bradbury, 2001)**.

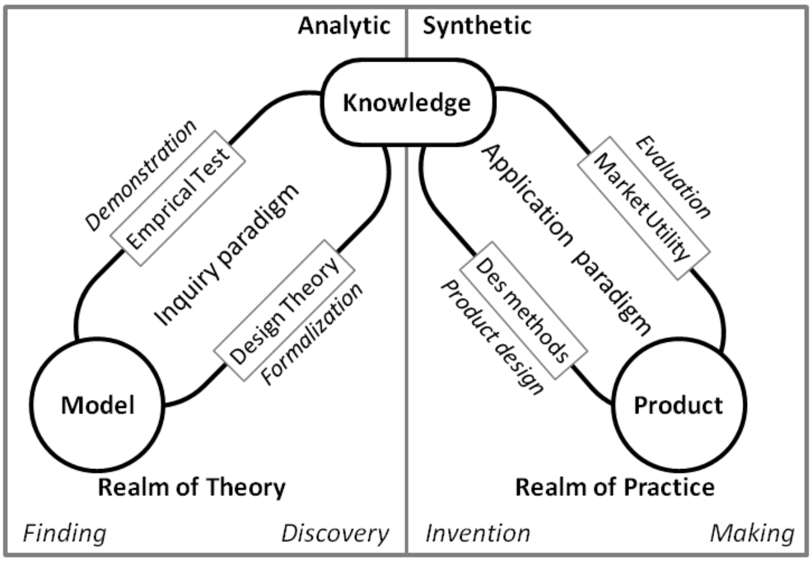


Figure 7. The processes of using and building knowledge in the two realms: a case of product design (Owen, 1998)

1.2.2 Emerging interdisciplinary theme: design cognition and emotion

The interaction among product, consumers, and designers is a core research subject in design (See Figure 8). Designers employ their expertise and experiences in conjunction with their cognitive and emotional aspects to product design. Consumer experiences products through their cognition, emotion, culture, etc. Until now, several studies have extensively focused on the cognitive and emotional aspects of consumers in relation to product/service. However, as we noted in section 1.1.1, the role of designers has recently been of great interest as for important contributors to the generation of the creative ideas that underpin efforts to meet consumers' needs and desires.

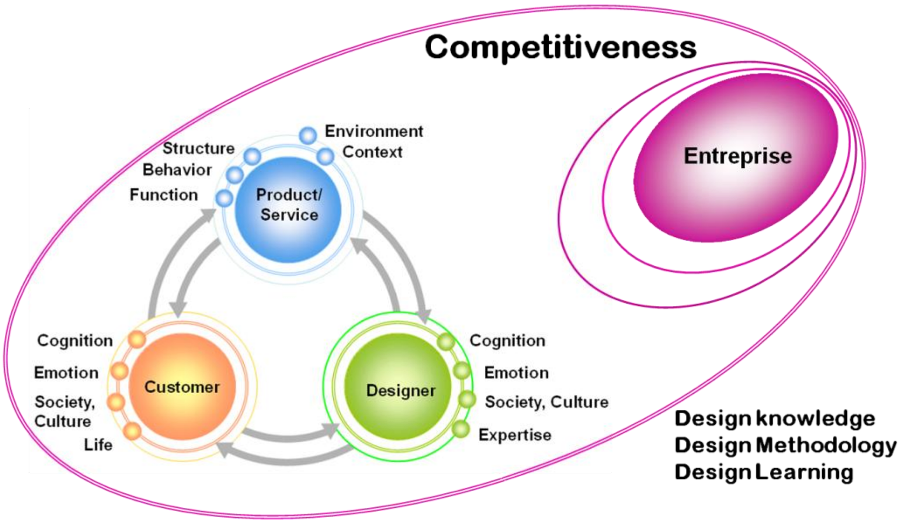
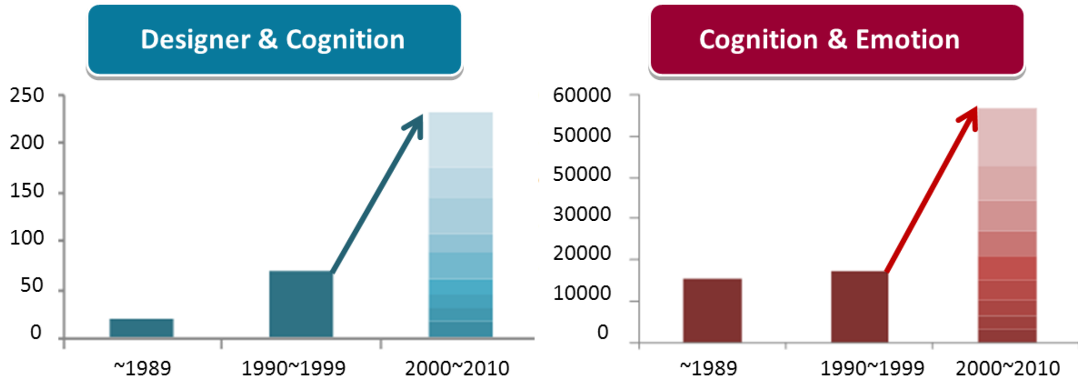


Figure 8. Product, customer and designer (Kim, 2009)

Design cognition refers to the process of design thinking **(Eastman, 2001)**. Understanding designer's cognitive activity in terms of human information processing has increasingly been studied in design, using different theoretical and empirical paradigms **(Simon, 1969; Schön, 1983; Gero, 2006; Bilda, 2006; Goldschmidt, 1994; Bouchard et al., 2003, 2008; Coley et al., 2007)**.

Figure 9a demonstrates the increasing number of publications regarding designer's cognitive activity. We sum up a number of articles including the two keywords: ''designer'' and ''cognition'' in their title or abstract in both ScienceDirect (www.sciencedirect.com) and SpringerLink (www.springerlink.com) on March 21, 2010.



(a) *(b)*

Figure 9. Growing interest in designer's cognitive activity and the relationship between cognition and emotion (Retrieved March 21, 2010 from Sciencedirect and Springerlink)

In accordance to growing interest in designer's cognitive activity, the study on cognition and emotion has been remarkable shifted in the past two decades in cognitive science. It was due to the recent emergence of behavioral and neuroscience data. Figure 9b indicates an increasing number of articles related to the subject of cognition and emotion. Therefore, understand designer's cognitive activity should be investigated in conjunction with emotional aspects of design. Figure 10 depicts that this interest has become a major interdisciplinary topic not only in design science, but also in psychology, computer science, etc.

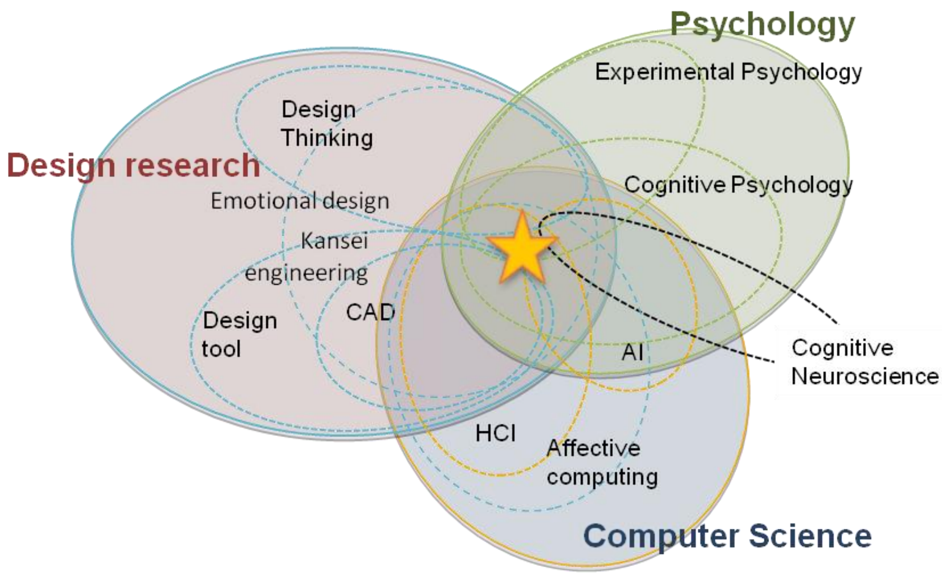


Figure 10. Understanding designer's cognitive activity as an Interdisciplinary topic

Psychology is concerned with all aspects of behavior and cognition, emotion, and motivations of humans and animals **(British psychological society, 2008).** Especially, cognitive psychology as a branch of psychology, explores the kind of knowledge that underlie human cognition and cognitive processes, including the study of memory, perception, memory, language, reasoning/decision making **(Cohen & Lefebvre, 2005)**. Cognitive psychology researchers often employed experimental methods, such as observation, interviews, brain imaging, and so on.

Computer science is concerned with digitalizing human cognitive process and with developing a computational tool. Especially, the field of artificial intelligence, or AI, understands and builds the 'computational' human intelligence, such as reasoning, thought processes **(Russell & Norvig, 2009)**. Affective computing is a new approach in artificial intelligence, aiming to develop computers that understand human emotional expression, affect **(Picard, 2000).**

The field of emotional design and Kansei engineering is also of great research interest. Emotional design is commonly used in design science, including **Norman (2002, 2004)**, **Desmet (2002), McDonagh & Hekkert (2003)**. They address that design carries some part of emotions, and it can elicit and/or motivate some emotions to the consumers/users. Kansei engineering is originated in Japan and progressively also appears in design science, including **Harada (1998), Nagamachi (2001), Schütte (2002).** Kansei is a human psycho-cognitive process related to human experience **(Lévi et al., 2007)**. Kansei engineering aims to accurately understand consumer Kansei; how to reflect and translate Kansei understanding into product design; and how to create a system and organization for Kansei orientated design **(Nagamchi (2001), cited in Scütte (2002)).**

1.2.3 Leading research groups in design cognition and emotion field

1.2.3.1 Outstanding laboratories in France and abroad

For many years, a number of research groups have done a lot of research in design cognition and emotion. This section does not intend to give a detailed list of universities and representative researchers, but rather to provide thematic, cultural differences in vision and competences. Table 1 lists several universities and leading researchers in the subject in France and abroad.

Some research groups have focused in the activities of interior and architectural design – such as in Austria and USA –; others have paid more attention to industrial designers, notably in Netherlands, South Korea, and Japan.

Table 1. List of leading research groups related to cognition, emotion, affecting computing in design

Nation	University/institution	Researchers	University/institution	Researchers
Japan	University of Tokyo	Nakakoji, Yamamoto	University of Tsukuba	Yamanaka, Lee
	JAIST	Nagai	Sapporo City University	Harada, Shiroma
	Kogakuin University	Shiizuka, Jue		
South Korea	KAIST	Lee, Norman (Visiting prof.)	Sungkyunkwan University	Young Se Kim
Taiwan	National Cheng Kung University	CHEN, DENG, MA		
France	University of Provence	Bonnardel, Marmèche	INRIA	Visser, Detienne
	University of Paris VI	Lesot, Bouchon-meunier	University of Paris VIII	Tijus, Chevalier, Levillain
	Arts et métiers ParisTech	Bouchard, Omhover, Aoussat	University of Paris XI	Darses
UK	Open University	Cross, Eckert, Garner, Lloyd, Prats	University of Cranfield	Roy
	University College London	Bianchi-Berthouze	University of Newcastle	Pearce, Lottum, Coleman
	University of Cambridge	Clarkson, Crilly	University of Bath	Howard
	Loughborough University	Porter	Cardiff University	Setchi
Netherlands	TU Delft	Hummels, Christianns, Keller, Pasman, Restrepo, Desmet, Hekkert	TU Eindhoven	Overbeeke, Levy, Dorst, Tomico
Sweden	Linköping University	Schütte, Dahlgaard		
Spain	Universidad Politécnica de Valencia (IBV)	Solves, Campos, Antacho	Universitat Jaume I	Vergara, Sancho-bru, Mondragón
Italy	University of Genova	Camurri		
USA	Krasnow Institute for advanced Study	Gero	Stanford University	Leifer
	Georgia Institute of Technology	Cai, Do , Lu, Eastman	University of Southern California	Jin, Chusilp, Benami
	Univ. Colorado	Fisher		
Australia	University of Sydney	Gero, Maher Candy, Bilda		

In France, rather than using the word ‘‘design’’, ‘‘conception’’ has more similar meaning to ‘‘industrial design’’ and widely employed. Historically, the activity of designers has been recognized and studied by several psychology researchers from the 1950s. To date, design researchers in France have gained insights from cognitive psychology, notably theories and methods related to human cognition, emotion, and creativity.

In the UK, based on a well-established infrastructure between universities and industry, their research in design covers mechanical engineering, affecting computing, interaction, etc.

The Netherlands hold the largest university-based design course worldwide, notably, TU Delft and TU Eindhoven, resulting in highly exploring work related to design experience, emotion, and computational tools.

In USA and Australia, notably, Prof. Gero J.S. leads a core research group on the study of design cognition and computation. He and his colleagues organize highly focused thematic conference every two years.

Besides the west side, several Asian countries, notably South Korea, Japan, and Taiwan, have promoted design research. Especially, design research in Japan has a strong focus on Kansei engineering from the 70’s. Their Kansei methodology and knowledge is not widely spread in the west, but it is starting to be shared by some pioneers in Europe. For example, in 2010, KEER conference (International conference on Kansei engineering and emotion research) moved for the first time in Europe, with the strong desire to push forward the exchanges between East and West on the topics related to Kansei.

1.2.3.2 Laboratory CPI: toward the optimization of design process

Our laboratory CPI (Product design and Innovation laboratory), Arts et Métiers ParisTech has been pioneering research toward modeling and optimization of the innovative design process **(Aoussat, 1990)**. Our study was designed to develop new models and tools to be used for digitalizing the early design process (See Figure 11). It consists of three progressive steps: (1) to identify the design knowledge, rules, and skills that underpin designers' cognitive processes **(Rasmussen, 1983)**; (2) to translate the design rules into design algorithms; and (3) to develop computational tools to be used by designers themselves and by other professionals involved in the early collaborative design process **(Bouchard et al., 2008)**.

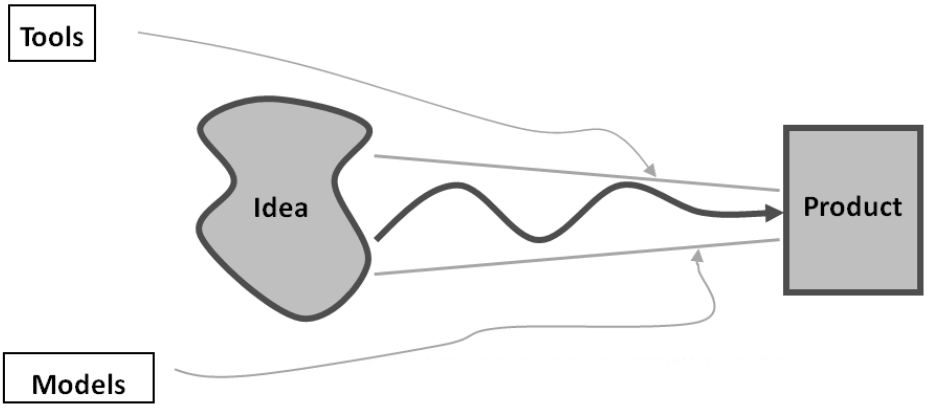


Figure 11. The need to develop new models and tools toward the optimization of design process (LCPI, 2005)

In our laboratory, this research framework was employed in a series of several interdisciplinary projects including:

- **KENSYS European project** (2003-2006, 1,41M€) was to develop Kansei engineering system integrating user's preference and emotional requirement.
- **TRENDS European project** (2006-2008, 5,0 M€) is to design an image-retrieval software, based on both image-content analysis and webpage's lexical content semantic analysis.
- **GENIUS ANR project** (2008-2011, 1,8M€) is to develop a system dedicated to the generative phase performed by designers, including the information categorization process and the generation of new formal solutions.

Especially, this thesis focuses on the first steps of research, which involve modeling those aspects of designer's cognitive and affective processes that are dedicated to the mental categorization of design information used during the generative phase. Moreover, the first part of experiments will be carried out within the GENIUS project. The detailed information is provided in section 4.1.1.

1.3 Conclusions

In creative society, designers have been considered as important contributors to the generation of creative ideas that underpin efforts to meet consumers' needs and desires. Their activities have led to a substantial increase in the value assigned to certain domains **(Resnick, 2007; Brown 2009)**. This new form of innovation has been referred as ''design-led innovation''. From both micro- and macroscopic views, many statistics demonstrated how the expertise and the cognitive and creative processes of designers during the early stages of design can lead to innovate and increase the competitiveness of an enterprise and nation **(Cox, 2005; BCG, 2009; EU report, 2009)**.

Indeed, there is a growing interest in the cognitive and emotional aspects of design during the early stages of design. The interest has become a major interdisciplinary topic not only in design science, but also in cognitive psychology, computer science and artificial intelligence field. A dissemination of information technology (IT) has led that designers developed digital design databases. It allows them to increase the access to a variety of solutions expected by consumer and to reduce the development timeline (**Pasman & Stapper, 2003; Büsher et al., 2004; Keller, 2005; Bouchard et al., 2008; Prats et al., 2009)**. However, it has been limited to prototyping technology dedicated to the detailed design process, even though the early stages of design consist of enormous, rich design information, which may enrich a software tool.

In this context, it is necessary to better understand designers' activities in the early stages of design process. Given that the activities of designers are relatively implicit and subjective and involve rich mental representations during the early stages of the design process **(Ullman et al., 1990)**, their formalization should be further investigated with an understanding cognitive mechanisms of designers in the thesis. Finally, it could be possible to develop computational tool in the early stages of design toward digitalization and optimization of the whole design process.

In order to do this, we intended to apply both an action research and laboratory-based experiments. This enabled us not only to build a model of the cognitive processes, but also to rely on both theoretical and experimental approaches to elicit the specific cognitive activities used by designers.

II. STATE OF THE ART

Introduction

There has been a rapid growth in the number of studies related to the designers' cognitive activity, and the link between their cognitive and emotional aspects in recent years. Therefore, it is necessary to provide a critical analysis of this work and to discuss how to measure and capture those implicit aspects of design.

According to **Cross (2007)**, design knowledge resides in three sources: people, process, and product. In our context, those sources can be interpreted as designer and consumers (people), early generative process (process) and early representations (product). Our state of the art brings together those three sources and structures them as shown in Figure 12.

The first section reviews both design research and cognitive psychology literature on designer's cognitive activity in the early stages of design. The second section brings together the previous design studies related to cognitive and emotional aspects in design, and aims to understand their interplay. A review of methods to analyse and measure designer's activity from cognitive to physiological methods is provided in third section. Chapter II is concluded by synthesizing the findings from scientific literature and delimiting the research problems. It finally leads to the formulation of a research question and the development of hypotheses in chapter III.

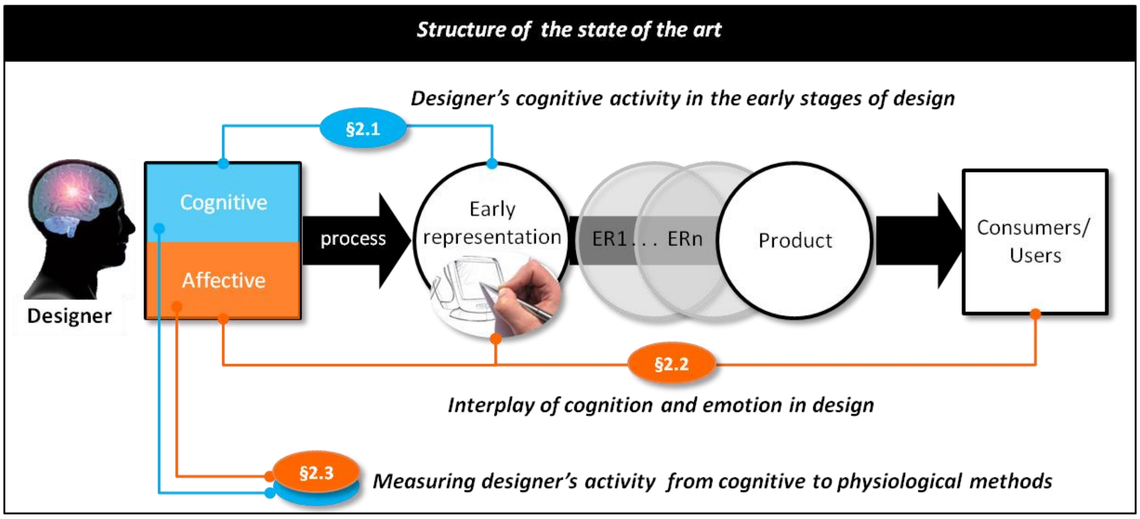


Figure 12. Structure of the state of the art

2.1 Designer's cognitive activity in the early stages of design

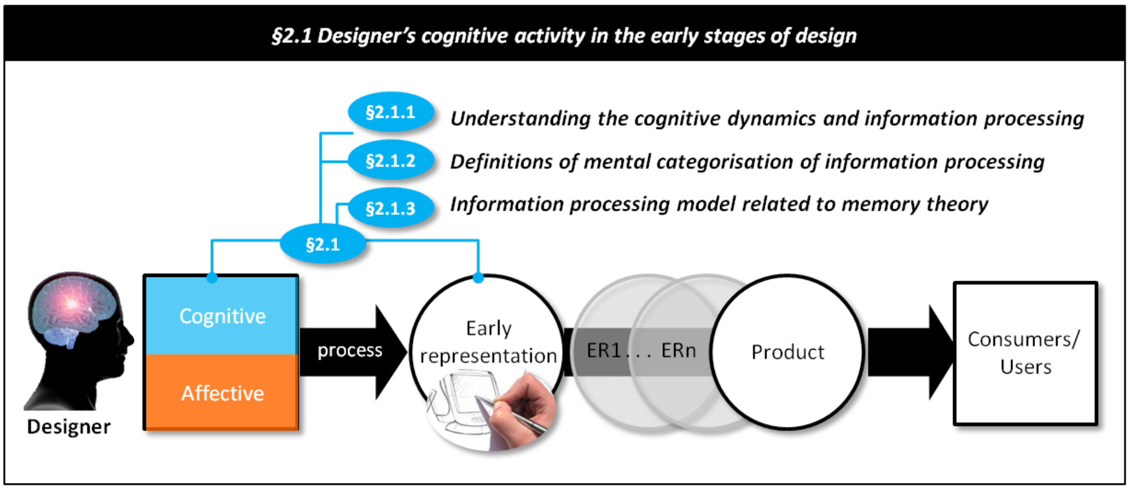


Figure 13. Structure of the section 2.1

2.1.1 Understanding the cognitive dynamics and information processing of designers

2.1.1.1 Three notions of designers' cognitive activities

Understanding design activity at a cognitive level has been acknowledged as an important research focus. Notably, the early stages of design are considered to be among the most cognitively intensive in the design process **(Nakakoji, 2005)**; so several studies have been developed on designer's cognitive activity, dedicated to the early stages of design process. The study of cognitive psychology leads to several internal cognitive processes, involving attention, perception, learning, remembering, speaking, problem-solving, reasoning, and thinking **(Eysenck & Keane, 2005)**. In design research community, designer's cognitive activities orient more towards three notions as follows:

- Problem-solving **(H. Simon, 1968)**
- Reflective-in-action **(D. Schön, 1983)**
- Construction of representations **(W. Visser, 2006)**

One of the widest research concerns designer's cognitive activity as a problem solving and information processing. **H. Simon (1968)** argued in his book ''The Science of the Artificial'') that

> *Design is inherently computational – a matter of computing the implications of initial assumptions and combinations of them* ***(Simon, 1968)***

In The Reflective Practitioner, **D. Schön (1983)** described design activities as a reflection-in-action. In reflection-in-action, the design practitioners' effort to solve problem yields new discoveries in the reflective conversation with the situation.

> *In ''reflection-in-action'', doing and thinking are complementary. Doing extends thinking in the tests, moves, and probes of experimental action, and reflection feeds on doing and its results. Each feeds the other, and each sets boundaries for the other* ***(Schön, 1983)***

W. Visser (2006) strengthened the importance of representation in design, not only external representations, including drawings or mock-ups, but also of mental representations. She defined design activities as a construction of representations until they become precise, concrete, and detailed.

> *Design consists in specifying an artefact[....] This specification activity consists of constructing [...] representations of the artifact until [these representations] are so precise, concrete and detailed that the artifact can be implemented* ***(Visser, 2006, 2010)***

In short, the consensual notion of design cognitive activity is that designers start with ill-defined or ill-structured problems in the early stages of design process; each problem solver (here, the designer) then constructs its mental representations of design problem which are mostly incomplete and imprecise in the beginning **(Simon, 1968)**. Designers integrate various intermediate representations (Physical or mental) to reduce levels of abstraction and degree of precision **(Bonnardel & Marmèche, 2005)**; mental representations of designers evolve as problem solving progresses. We could find reflexive conversation between the designer's mental representations and externalized representations (e.g. early sketches). This mechanism is referred as to 'Seeing-Drawing-Seeing' cycle **(Schön & Wiggins, 1992)**.

2.1.1.2 Use of physical and mental representations

Given that the early stages of the design process used to be characterized in terms of information processing and idea generation (also called “conceptualization”), several researchers have investigated on the explicitation of representations in design and formalization of designer’s cognitive processes. **Bouchard et al. (2003)** interpreted the cognitive processes of designers during the early stages in terms of informational cycles. According to this view, designers engage in an informational cycle that includes informative, generative, and evaluative phases (decision-making) to produce intermediate representations (IRs) that develop in an evolutionary way. Figure 14 shows a list of representative researchers on this subject; they are positioned in the framework of **Bouchard et al. (2003)**. In the early stages of the design process, it is hard to find formalized objects. This is why the notion of intermediate representations (IRs) has to be introduced.

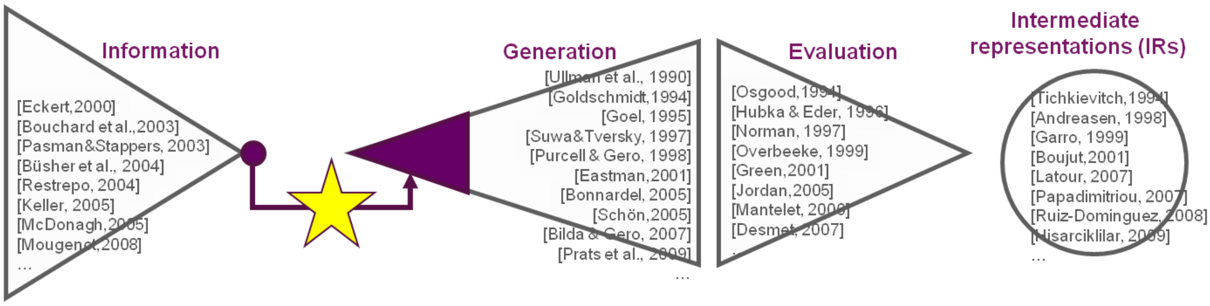
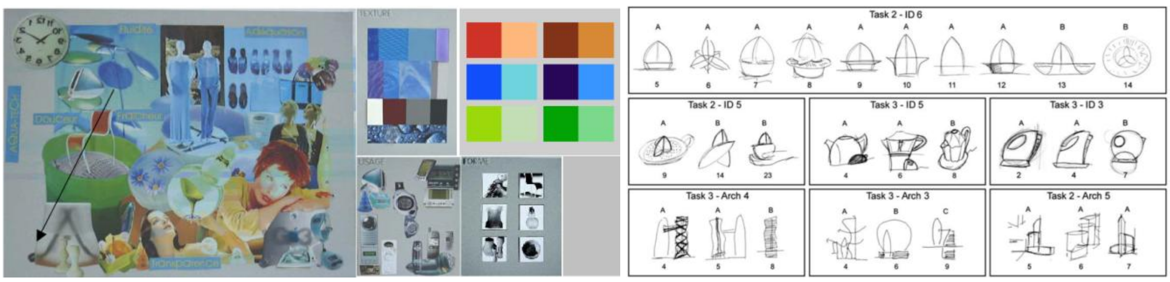


Figure 14. Information cycle with a list of representative researchers (not exhaustive)

Goldschmidt (1994) defined ‘‘intermediate representations’’ as mental or physical images used during the whole design process. IRs can be implicit or explicit, appearing as design briefs, trend boards, 2D/3D sketches, styling models, digital geometrical models, mock-ups, prototypes, and so on (see Figure 15). They are used strategically according to the design context, design phase, design purpose, cultural context, and so others.



(a) *(b)*

Figure 15. Examples of early representations: (a) TRENDS Board and form-colors-texture pallets (Bouchard et al., 2008), (b) early sketches (Prats et al., 2009)

Several studies on interior and architectural design have focused on the sketching activities of designers, especially those that are performed during the generative phase **(Schön & Wiggins, 1992; Goldschmidt, 1994; Suwa & Tversky, 1997; Bilda & Gero, 2007; Prats et al., 2009)**. Since the early 1990s, a few studies dedicated to the sketching activity of designers have emerged in mechanical engineering design; these include **Ullman et al. (1990), Goel (1995), Purcell & Gero (1998), Boujut & Blanco (2003), Yang (2009)**. To date, little research has addressed issues related to the inspirational sources used by designers in the informative phase (**Eckert & Stacey, 2000; Keller, 2005; Bouchard et al., 2008)**.

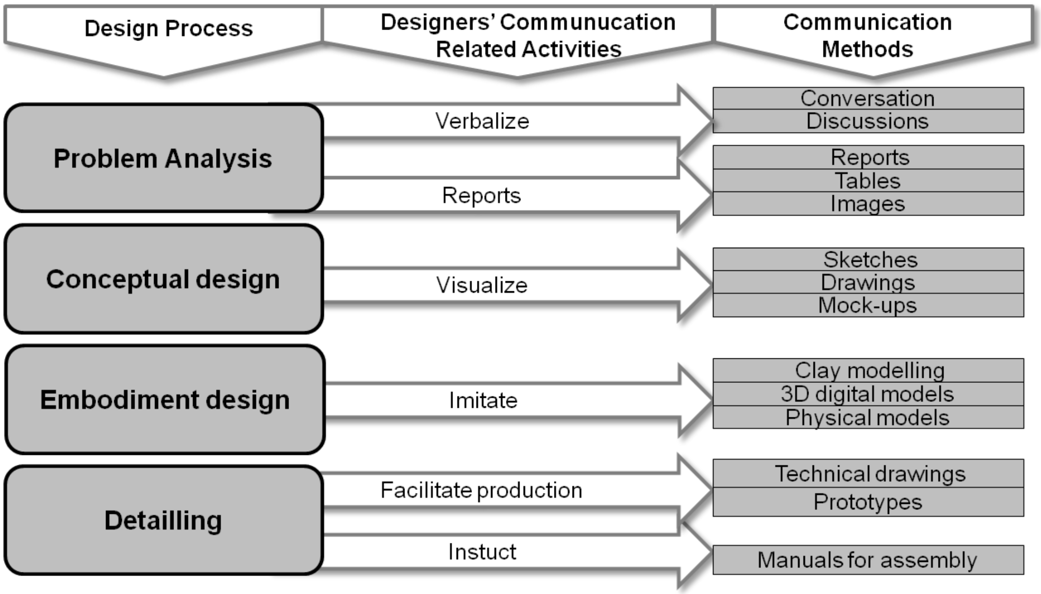


Figure 16. Design process, designers' communication related to activities, and communication method (Özcan & van Egmond, 2006)

As seen in Figure 16, designer's communication by means of representations is very limited to verbalizing, reporting, visualizing, etc. Since much design research depends on explicit activities from empirical studies; therefore, the explicit representation is relatively well established **(Coley et al., 2007)**. However, mental representations of designers and internal process are hard to be extracted and formalized. Moreover, the bridge between the informative and earliest generative phases has been relatively neglected. Recently, some pioneers have stressed out the need to define the specific internal processing and the important role of mental information. **Restrepo (2004)** found that designers sometimes completely ignore other external information sources, when they develop ideas, i.e. they can generate ideas without the aid of external representations as the images sources. **Bilda (2006)** has confirmed that the use of imagery alone can support idea development as well as sketching does. Nevertheless, some questions still remain on the different purpose and efficiency of the use of various levels of design information to generate ideas.

2.1.2 Definition of the psychological processes whereby design information is categorized

2.1.2.1 Bridge the informative and early generative phases with mental representations

The bridge between the informative and earliest generative phases involves the generation of new ideas and new solutions. It begins with numerous mental images, memorized design briefs, and other information deriving from previous design projects **(Bouchard et al., 2003)**. During the earliest generative phase, certain parts of the mental images can be externalized in sketches. These early sketches are not mature or suitable to be shared with or interpreted or used by other people. Instead, they can be used as external representations (i.e., externalized memories that act as visual tokens during later inspection) **(Goldschmidt, 1994; Suwa & Tversky, 1997; Crilly et al., 2008; Prats et al., 2009)**. External representations (e.g., early sketches) allow a reflexive conversation between the designer and the product to be created **(Crilly et al., 2008; Suwa & Tversky, 1997)**. Previous studies have shown that external representations allow designers to identify errors that are then used to generate new ideas **(Akin, 1978)**. Similarly, **Crilly et al. (2008)** noted that designers engaged in “bi-directional conversations” with representations insofar as design intentions were formed and reformed during the activities of representation, like as “Seeing–Drawing–Seeing model” **(Schön & Wiggins, 1992)**. They help designers structuring mental representations and also arguing the generation of design solutions. This process has been recognized as an individualized experience for designers that manifests in repetitive cognitive activities **(Jin & Chuslip, 2006)**.

As shown in Figure 17, **Ullman et al. (1988)** defined design state as a location, which consists of short-term memory, long-term memory, and extended memory. Extended memory includes pieces of notes, sketches or CAD tools. During design, part of design state is stored in long-term memory through short-term memory; mental information stored in long-term memory then can be externalized into the type of extended memory later on.

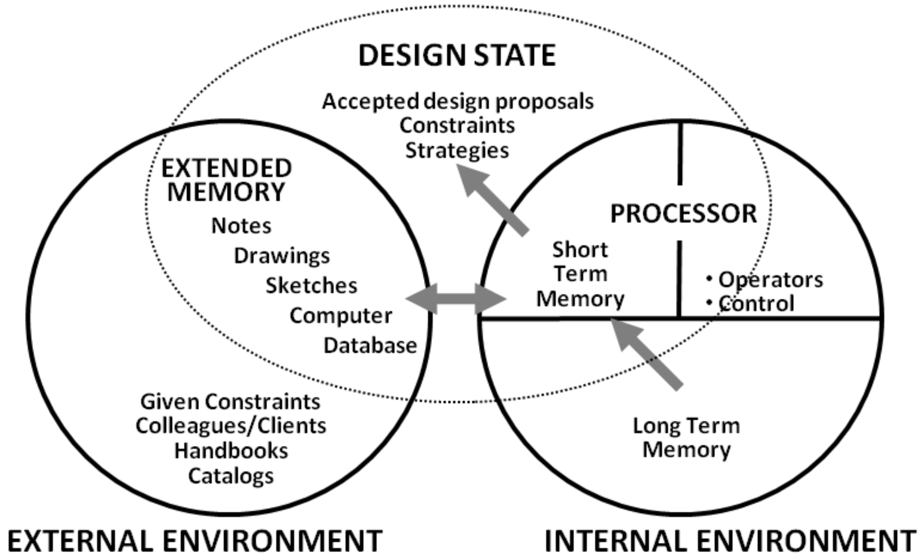


Figure 17. The design environment - External/Internal (Ullman et al., 1988)

Similarly, a conceptual model of **Eastman (2001)** consists of a designer's conceptual world (the design and its context) and external world (external objects and observations). His model also explains a constructive designer's conceptual world over time, using the designer's already gained knowledge and experience and from external sources of information (See Figure 18).

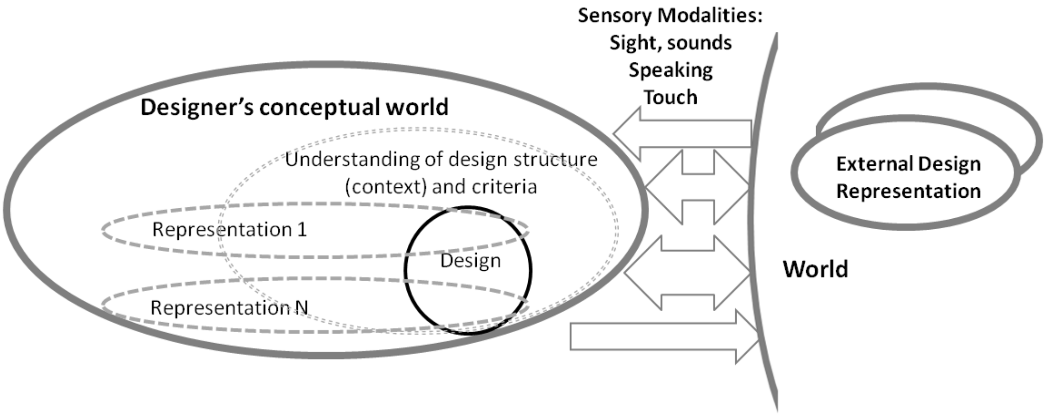


Figure 18. A designer's conceptual world and external world (Eastman, 2001)

Gero (1999; 2004) and his colleagues have formalized design phenomenon by introducing the notion of ''constructive memory and situatedness''. Figure 19a depicts this conception where memories are constructed from experience and earlier memories that in turn become part of the situation that affects the kinds of memories that can be constructed **(Gero, 1999, p.32)**. Given the notion of ''constructive memory and situatedness'', a situated function-behavior-structure (FBS) framework has been developed (See Figure 19b). The FBS framework represents a model of designing by eight processes in relation to function, behavior, and structure together. Among the process, our interest is the reformulation of the design state spaces (processes 6-8) because 'reformulation process' implies that the design process is an on-going process. The definition of reformulation is ''changes in the design state space in terms of structure/ behavior/ function variables or ranges of values for them if the actual behavior is evaluated to be unsatisfactory'' **(Gero & Kannengiesser, 2004, p.375)**.

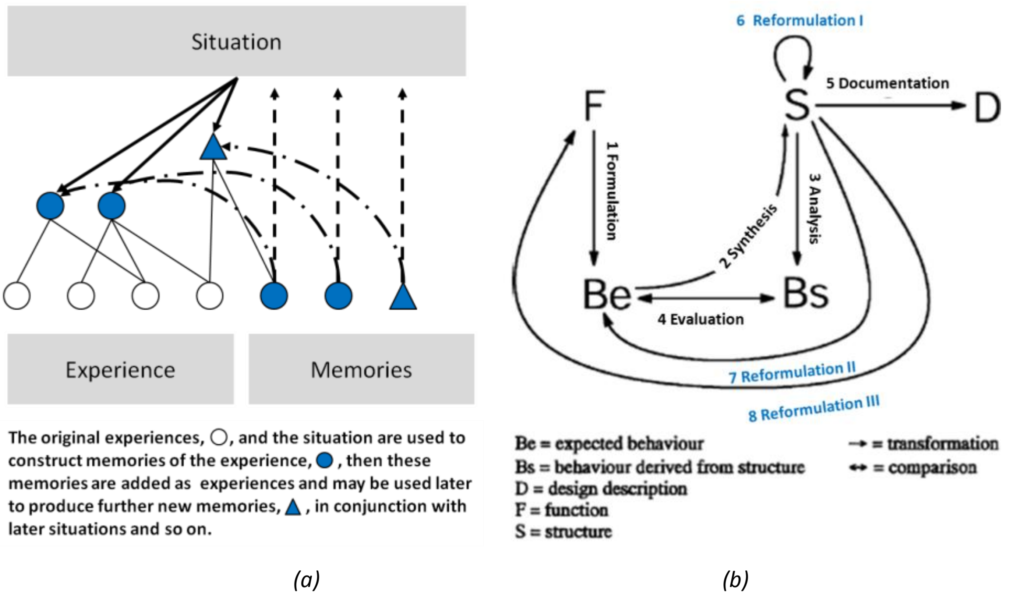


Figure 19. (a) Constructive memory and situatedness (Gero, 1999), (b) FBS framework (Gero & Kannengiesser, 2004)

In summary, as several cognitive psychology and design researchers pointed out, designers need to create multiple representations at different levels of abstraction (mental, physical) in order to support their cognitive processes. Especially, designer's internal processing with mental information plays an important role in conjunction with externalization process (sketching). However, the research advances on mental information in the generative phase have not yet come to the fore.

2.1.2.2 Definition of 'mental categorization of information processing in the generative phase'

A cognitive operation, 'categorization' has been the central question for decades in cognitive science because it is the clue to understand how we perceive and categorize information. A significant interest on 'categorization' was shown in several workshop and publications. Notably, in 2003, the summer institute on ''categorization'' took place at the Université du Québec in Montréal. Handbook of categorization in cognitive science (edited by **Cohen & Lefebvre (2005)**) has been issued as a result of this summer institute on ''categorization''. They try to define ''categorization'' in interdisciplinary contexts, including anthropology, computer science, linguistics, neuroscience, philosophy, and psychology. A consensus on the definition of 'categorization' in cognitive psychology is that ''Categorization is the mental operation by which the brain classifies objects and events **(Cohen & Lefebvre, 2005)**.''

During the design process, external and mental information interact with each other in an evolutionary manner. Those design information are gradually integrated and synthesized into various levels of categories contributing to design solutions via the designer's mental processing. In this respect, we define this phase 'mental categorization of information processing in the generative phase', which involves the psychological process whereby design information is categorized during the sketching.

Here we give definitions of key terms used in this thesis: the mental categorization of information processing, the generative phase, generation of early sketches (See Figure 20)

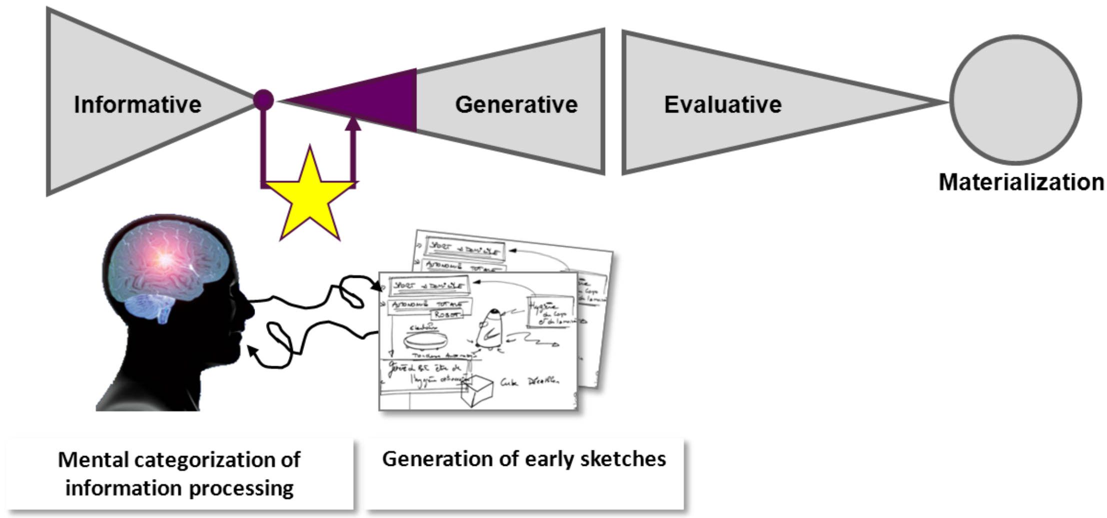


***Figure 20*. The mental categorization of information processing in the generative phase**

- **The mental categorization of information processing** is the phase where designers employ various levels of mental information, and gradually integrate, structure, and synthesize them into their memory in order to further generate early sketches.

- **The generative phase** is characterized by the production of sketches to find a ''good form'' of one or several concept(s). Certain parts of the mental images can be externalized in sketches during this phase.

- **Generation of early sketches** is the first externalization of this mental information of designers. These early sketches are not sufficiently mature to be shared, interpreted, or used by other peoples. Instead, they can be used as external representations of the designer himself.

In design practice, even though the purpose on mental categorization of information processing might be different depending on the context of application, the mental categorization processing can provide an unique opportunity to see how the designer's needs for information are shaped by the information already accessed **(Restrepo, 2004)**. In addition, it is very specific inasmuch as it includes the ability to diverge and to generate new categories and to converge and classify image resources to fit in existing categories at once. Moreover, in observing design activities, we could find that designers try to discover a 'new' or 'previously hidden' association between a certain piece of information and what they want to design **(Sharples, 1994)**.

Hence, the aim of this thesis is to identify the kind of cognitive operations that extract design information from memory and to determine how this design information is transformed or categorized during early sketching. Toward this goal, the following section proposes an initial descriptive model of information processing that integrates memory models derived from cognitive psychology, which describe the transfer of information through memory, including those of **Broadbent (1958), Atkinson & Shiffrin (1968),** and **Baddeley, Eysenck, & Anderson (2009)**.

2.1.3 Information processing models related to memory theory

2.1.3.1 Introductory memory theory

Figure 21 shows an initial memory model ''three stages of memory ''developed by **Atkinson & Shiffrin (1968)**. This model was the matrix of the basic architecture of the memory system. It describes information flows from environment through sensory memory and short-term memory to long-term memory.

The following definition of memory stores was extracts from 'MEMORY' edited by **Baddeley, Eysenck, & Anderson (2009).**

- **Sensory memory (SM):** a term applied to the brief storage of information within a specific modality
- **Short-term memory (STM):** a term applied to the retention of small amounts of material over periods of a few seconds.
- **Long-term memory (LTM):** a system or systems assumed to underpin the capacity to store information over long periods of time

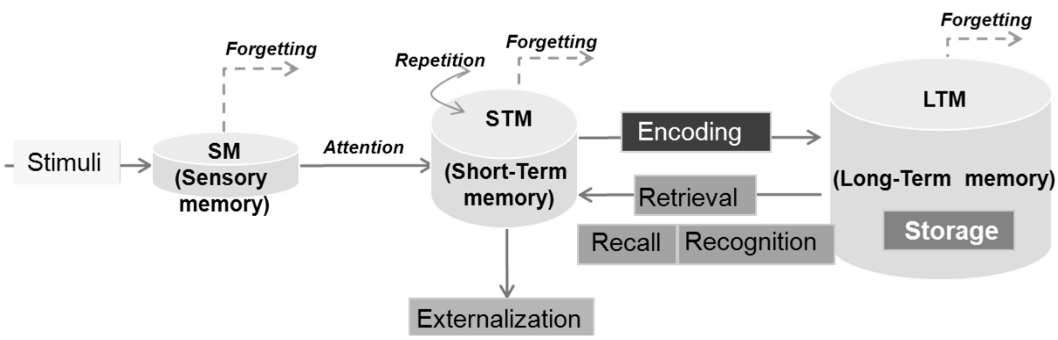


Figure 21. Three stages of memory model (Atkinson & Shiffrin, 1968)

Here, we superpose a memory model on the informative and generative phases of the design process, in order to understand memory processing in context of design (see Figure 22). We divided its dimensions into external/internal processes and informative/generative phases. The external information stimulates Sensory Memory (SM) and then the information is transferred from short-term memory (STM) to long-term memory (LTM). Information should be encoded in a type of chunk to enter into LTM. LTM stores information as an associative network with nodes and links. A node may contain concepts, words, images, or any other information, and a link represent an association between two nodes **(Atkinson & Shiffrin, 1968; Dix et al., 1993; Croft, 2004)**. Then, categorized information in LTM can be retrieved through 'recall' or 'recognition' operation. During recognition the existing information comes out from LTM; during recall, the information is reproduced, as new information.

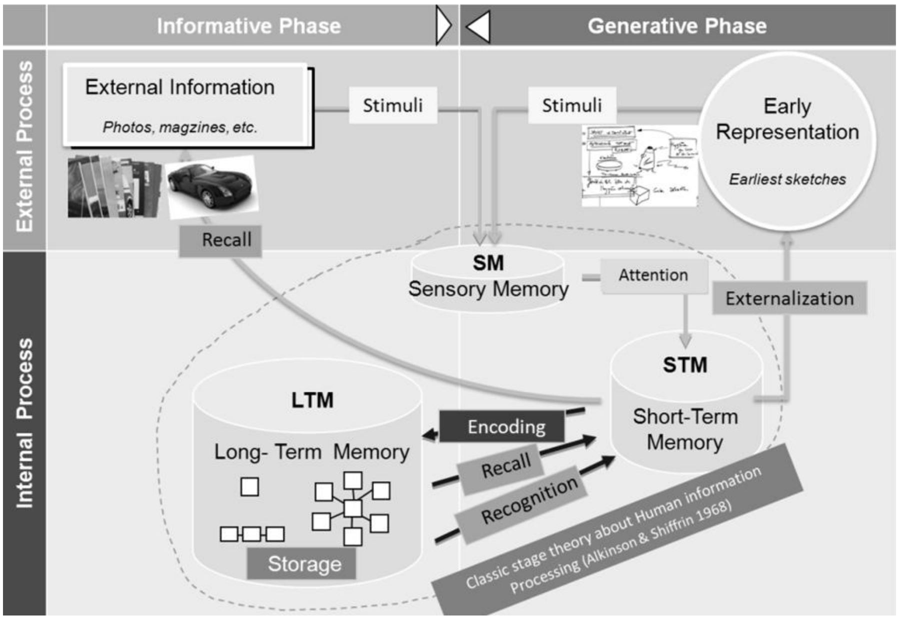


Figure 22. Descriptive model of information processing to generate ideas (Kim et al., 2009a)

Given that we are interested in mental categorization of information processing as the internal processing, we found the strong similar cognitive mechanism of mental categorization of information processing linked to long-term memory (LTM), like as designers did in design practice. Especially three cognitive operations - Encoding, Storage, Recall which are linked to LTM strongly were of great interest. The definition of these three cognitive actions in cognitive psychology is as follows **(Atkinson & Shiffrin, 1968; Dix et al., 1993)**.

- **Encoding:** the conversion of incoming information into a form that can be stored in memory.
- **Storage:** retaining information in memory over time.
- **Recall:** information reproduced from memory can be assisted by cues e.g. categories , Imagery

In the next section, we describe more advanced and complex memory models with an information processing approach. It allows us to define detailed cognitive operations to understand mental categorization of information processing performed by designers.

2.1.3.2 Advance memory model in relation to cognitive operations

The information processing approach was introduced in the 1950's. Memory models have evolved with more components in conjunction with their level of complexity. Table 2 and Appendix B provide famous memory models related to information processing.

Table 2. Human information processing models

	Authors (year)	Model
1	Broadbent (1958)	Filter Model of Selective attention
2	Atkinson & Shiffrin (1968)	Three stages of Memory
3	Craik & Lockhart (1972)	Level of processing
4	Baddeley (1974, 2000),	Multi component working memory model
5	Lindsay & Norman (1977)	Information processing model
6	Warrington & Taylor (1978)	3-stage theory of object perception
7	Card, Moran, & Newell (1983)	GOMS model
8	Paivio (1986)	Dual coding theory
9	Cowan (1988)	Embedded-process model of working memory
10	Harris (1992)	Components of human information processing
11	Finke, Ward, & Smith, (1992)	Geneplore Model
12	Kosslyn (1994)	Protomodel of visual object Identification
13	Logie & van der Meulen (1995)	Multicomponent working memory model
14	Ball & O'Callaghan (2001)	A Statement-Level Analysis
15	Jin & Chusilp (2006)	A cognitive activity model of conceptual design
16	Kurosu (2010)	Cognitive-emotional processing model (CEP)
17	Goldschmidt (2010)	Designer-memory-stimuli model (DMS)

Broadbent (1958) proposed a sequence of cognitive processing stages that can be performed in bottom-up or top-down order. Bottom-up processing is considered as a stimulus-driven process caused by a sensory stimuli, whereas top-down processing is seen as memory-driven. In many cases, stimulus-driven processes are based on inspiration such as photos, magazines, and so on, which evoke feelings or emotions. Memory-driven processes are driven by knowledge derived from past experiences.

According to the Geneplore model defined by **Finke et al. (1992)** in the work of **Benami & Jin (2002)**, several types of cognitive operations underpin the generative phase: retrieval of information from memory, association, mental synthesis, mental transformation, analogical transfer, and categorical reduction. More specifically, operations connecting between working/short-term memory (WM/STM) and long-term memory (LTM) play important roles in retrieving memorized design information. Several of these, including mental synthesis and reduction, are difficult to categorically identify through verbalizations or sketches, but the remaining three (retrieval of information from memory, association, and transformation) can usually be identified.

More recently, **Goldschmidt (2010)** tried to bring together design process and memory by connecting designer, memory, and stimuli. This model focuses on the architecture of memory and its activation, in conjunction with the role of stimuli in design creativity. Figure 23 extracts a specific link between designer and memory. The attention to a stimulus causes activations; the pattern of attention may be defocused (flat activation) or focused (spiky activation) ones. Given that designers have a flexible ideas between divergence and convergence approaches, defocused attention is likely to have more retrieval opportunities; therefore, it helps designers generate conceptual fluency in the designer's search for novel ideas.

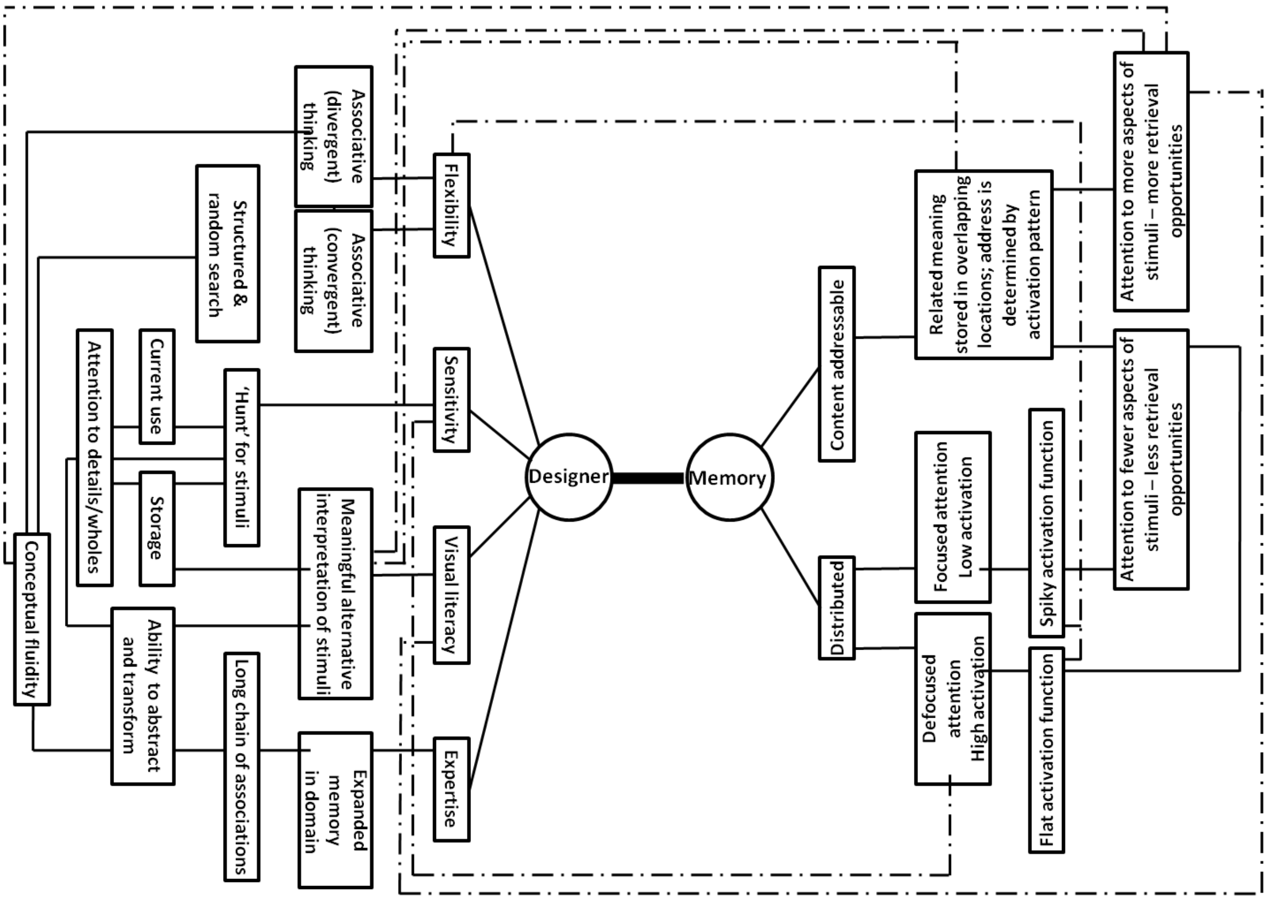


Figure 23. Designer-memory (DM) links (Goldschmidt, 2010)

In the field of Kansei information, **Kurosu (2010)** presented the CEP (cognitive-emotional processing) model where the emotional process is superposed to the cognitive processing model (see Figure 24). Considering that the traditional information processing model of cognition have been understood by being distinct from the model of emotion, except for those of **Roseman(1984), LeDoux (1986), Forgas (1995), Mogg & Bradley (2005),** etc., the CEP model is very interesting to understand how emotional process can be overlaid over the cognitive processing. As shown in Figure 24, the emotional process can be divided into two: one is the extrinsic emotional process that reacts to the stimuli (sensory input); the other is the intrinsic emotional process that emerges without any stimulus. Most of the emotional process is not the data flow, but control flow in contrast to the cognitive processing. **Kurosu (2010)** thought that the level of valence may trigger the emotional process in a positive or a negative way. Moreover, the pair of information and valence will be stored to the LTM for possible retrievals.

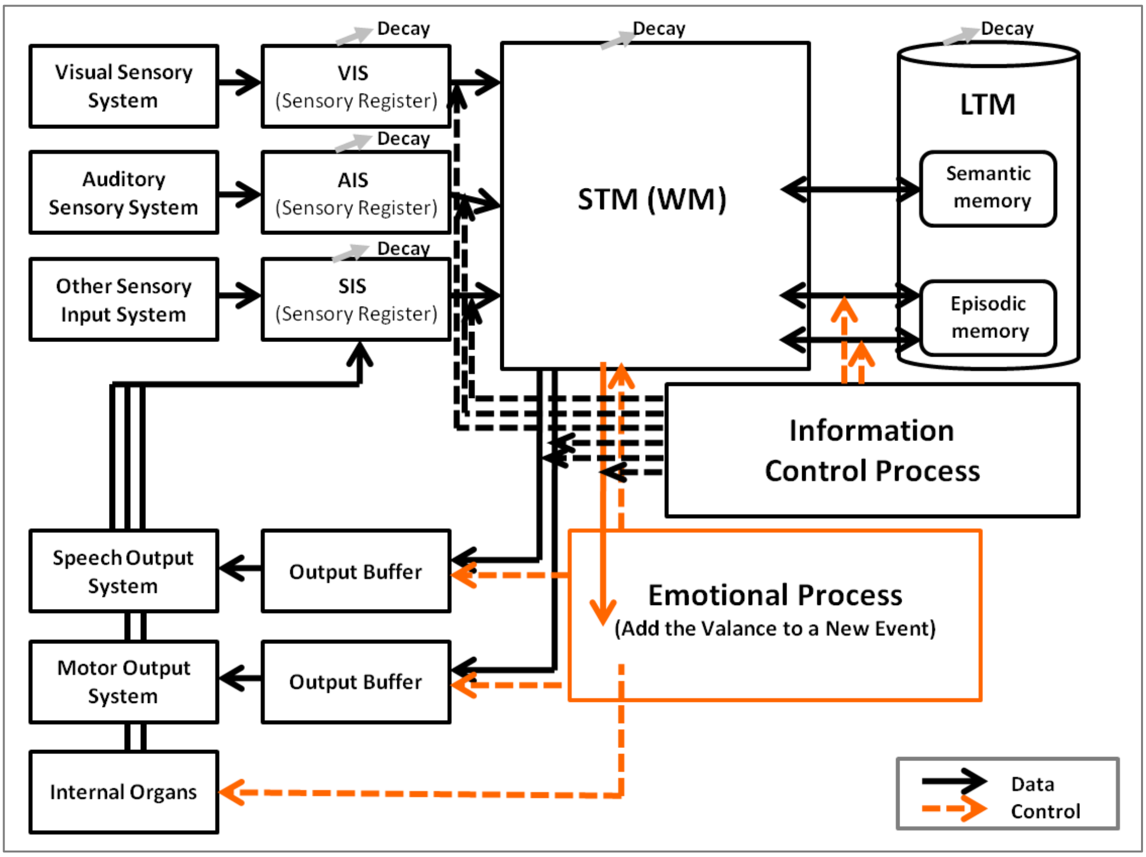


Figure 24. Cognitive-emotional processing model (CEP) (Kurosu, 2010)

Finally, we focus particularly on memory-driven processes, which have received relatively less attention. This internal information processing still remains less understood due to their implicit nature, characterized by information stored in memory as well as cognitive operations related to such information.

2.1.4 Synthesis: the need to formalize a cognitive model dedicated to mental categorization of information processing

In section 2.1, we described the cognitive aspect of designers and its processing in the early stages of design. Given that the early stages of design are considered to be among the most cognitively intensive in the design process and its early phases to generate new ideas, several studies have been progressively trying to formalize and develop a cognitive model of these; however, some phases of the early stages of design are still remained incompletely understood. It is due that much design research depends on the findings from the empirical studies **(Coley et al., 2007)**. Therefore, these studies have neglected the cognitive aspects involving construction, categorization of design information for idea generation in the early stages of design. In this thesis, we defined this phase as 'mental categorization of information processing' where designers mentally categorize design information in order to generate early sketches. This phase will bridge the gap between the informative and earliest generative phases.

Then, how can we explicitly make a model of 'mental categorization of information processing'? As **Finger & Dixon (1989)** and **Takeda et al. (1990)** pointed out, design process can be modeled progressively: descriptive, cognitive, and finally computable (See Figure 25). Proposing a descriptive model helps us to clarify and define what design is from a theoretical point. Furthermore, it will be essential to develop a cognitive model of design process. As shown in section 2.1.3, a descriptive model of information processing involving memory theories drawn from cognitive psychology will be refined and enriched via an empirical study.

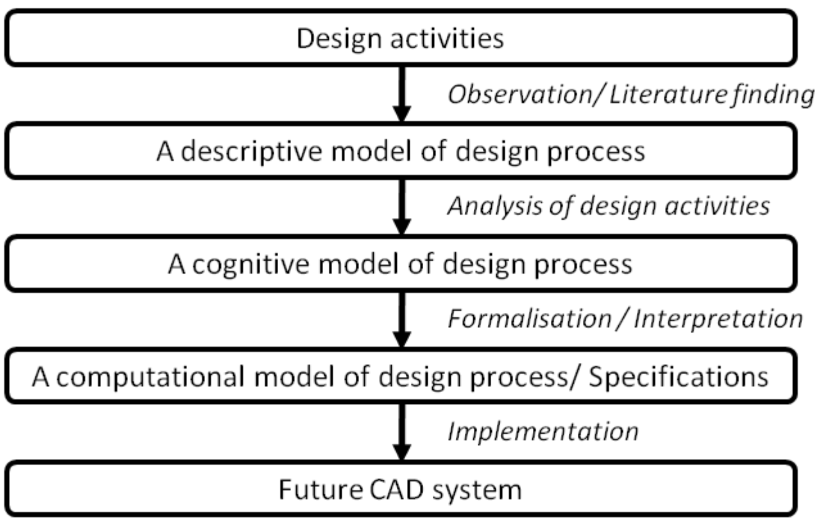


Figure 25. Research framework (modified from that of Takeda et al. (1990))

2.2 Interplay of cognition and emotion in design

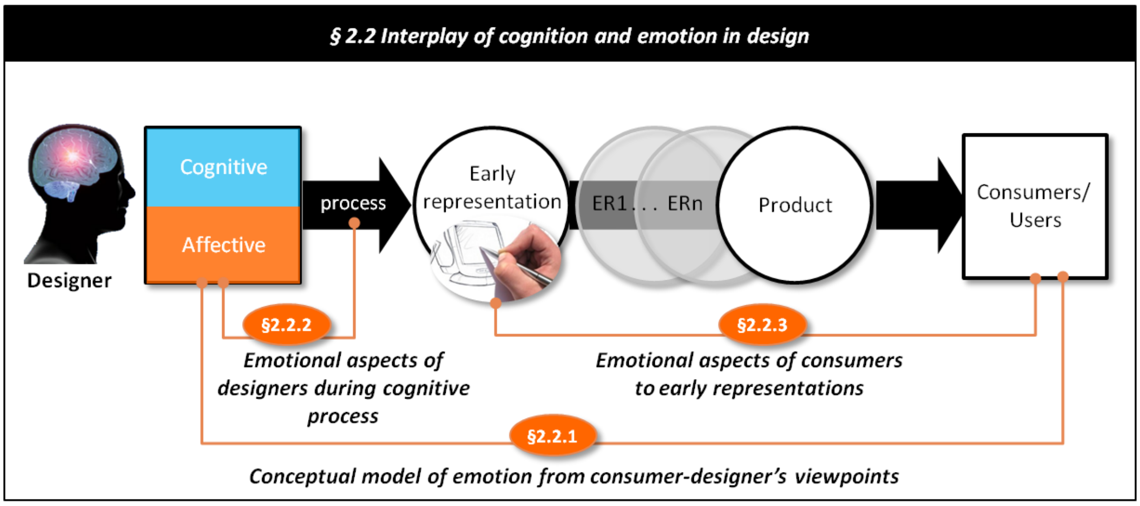


Figure 26. Structure of the section 2.2

In cognitive science and psychology, the study on cognition and emotion has been remarkably arising in the past two decades. Before, several studies were focused on 'cold' cognitive process – ranging from decision-making to memory, nowadays rich areas of research have been emerging on the interplay of cognition and emotion **(Phelps, 2006; Ochsner & Gross, 2007)**. Expanding this movement into design, **Norman (2004),** and **Desmet & Hekkert (2007, 2009)** have been the first to explore the relationship between emotion and design. Since then, the study on emotional design is of great interest in design and also in cognitive psychology. A review of the psychological literature on *the emotional brain* by **Ledoux (1998)**, argued that cognition and emotion are unified and contribute to the control of thought and behavior conjointly and equally. **Ellsworth & Scherer (2003)** stated that emotional reactions typically involve extensive cognitive processing.

Figure 27 illustrates the relationship between affect and cognition. **Helander & Khalid (2006)** and references therein thought that people perceived stimulus by means of two systems: affective system and cognitive system; both systems are not separated. Affective system relies on cognition and vice versa.

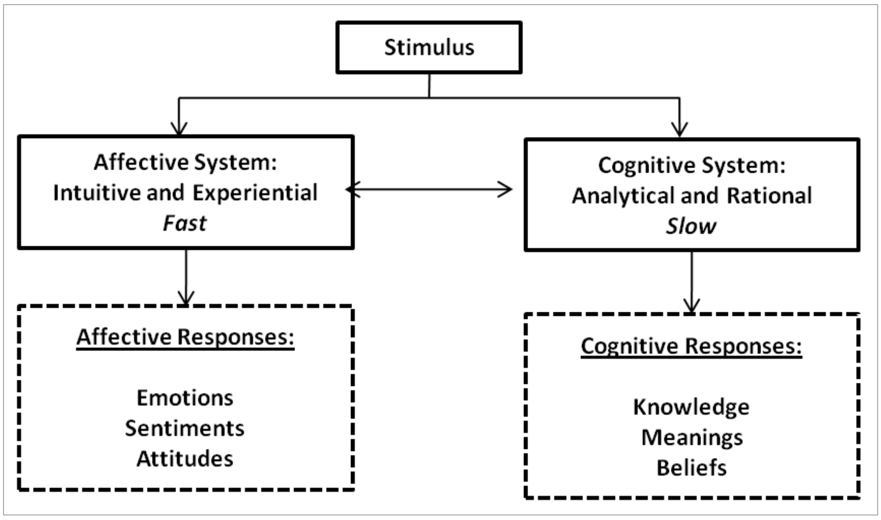


Figure 27. Coupling of affect and cognition (Khalid, 2006)

In design practice, according to our recent survey with 40 professional automobile designers **(Bouchard et al., 2009)**, the designers recognize that their activity deals with emotional content (See Figure 28). Designers naturally and intuitively are conscious of the emotional impact on their cognitive activities to provide design solutions characterized by their semantic expression, but they are not able to assess precisely their effect **(Bouchard et al., 2009)**.

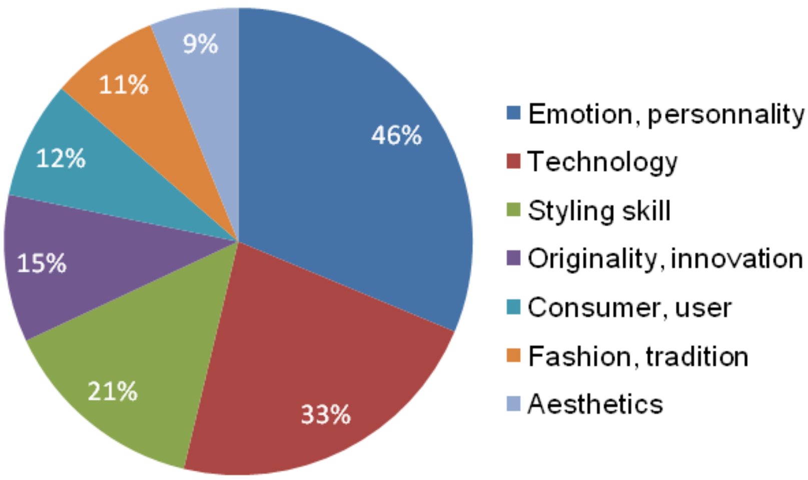


Figure 28. Dimensions treated, perceived in car design (Bouchard et al., 2009)

In addition, emotional reactions with nonlinguistic expression, such as laughs, sighs, yawns, etc., can also be found in design activity. Especially, positive reaction like as 'WOW effect' is helpful in the understanding of the product and its use. After **Norman & Ortony (2003)**'s definition, 'the wow effect' resides more in the visceral responses of the user primarily result from the immediate emotional response to the look or feel of the product in positive cases. **Hazlett & Benedek (2007)** claimed 'wow effect', as positive emotional spike when an individual is offered an experience by the product that is different from or more than what they expected. However, this is not what is meant in this thesis. We intend to use 'wow effect' from designer's point of view. **Cuisinier (2010)** explained that incident emotion appears to be one goal among designers: by provoking an emotion, they arouse a desire to approach an object or situation.

2.2.1 Conceptual model of emotion from consumer-designer's viewpoints

With the emergence of emotional design and Kansei engineering, for more than a decade, several researchers proposed theories and models in order to understand emotion in design **(e.g. Noman (2004), Desmet & Hekkert (2007; 2009))**. In a broader view, Kansei is somewhat a human psycho-cognitive process related to human experience **(Lévi et al., 2007)**. Until now, however 'Kansei engineering' is limited to determine subjective estimations of products and concept properties by the reactions from customers/users **(Schütte, 2002; Lévi et al., 2007)**. It neglected designer's emotional impact in their cognitive activity in the early stages of design. However, understanding emotion in the perspective of both designers and consumers is of great interest. Some pioneers have recently proposed models and theories; these include those of **Khalid (2006), Ho & Siu (2009),** and **Crilly et al. (2009)**. In the following section, we will briefly outline three conceptual models, which contain both sides of consumer's and designer's emotion.

Ho and Siu (2009) have investigated some taxonomy related to emotion in design. As Figure 29 shows the whole process of emotion flow, there are interactions between the designers and the consumers through design outcome. ''Emotional design'' is commonly used in design science, it concerns that designs carried out some part of emotions, or the form and appearance which can elicit and/or motivate some emotions to the users. This term understands emotion in the perspective of consumer's vis-à-vis design outcome. In designer perspective, designers inject their emotions in designing an outcome; it is referred to as ''Emotionalise design''. Finally, ''Emotion design'' covers both ''Emotional design'' and ''Emotionalise design'' by taking into account both perspectives of designers and users.

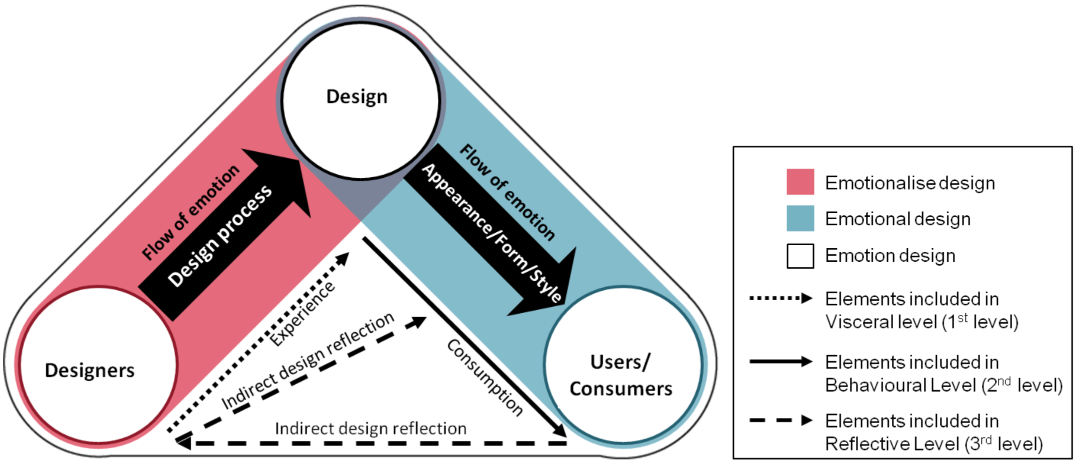


Figure 29. Model of the relationship between "emotionalise design" and "emotional Design" (Ho & Siu, 2009)

According to the framework of affective user-designer model developed by **Helander & Khalid (2006)**, two parts concerned: the designer's environment and the affective user, so as to illustrate how a designer may achieve affective design and how the user will receive, perceive and react to the design (see Figure 30). Designer's environment consists of subsystems: artifact, context of use, and society trends. Especially, amongst artifact subsystem, they pointed out affective quality of designers, which is the ability to cause affect, feeling, and mood. For example, how pleasant –unpleasant, or exciting boring, etc.

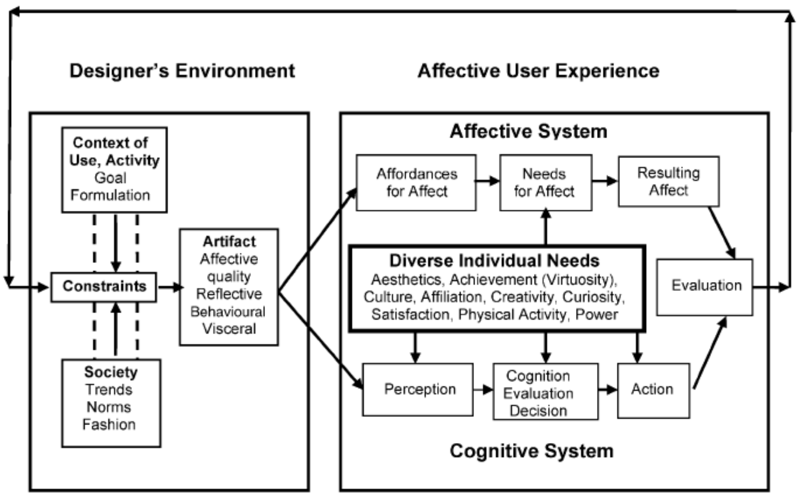


Figure 30. A framework of the affective user-designer model (Helander & Khalid, 2006)

Crilly et al (2004, 2009), have developed a conceptual framework for product form representing designer intent and consumer response (See Figure 31). The consumer responses to a product form were initially investigated by means of cross-discipline literature reviews (right part); designer's intention to product form was studied based on the qualitative results from semi-directive interviews of 23 industrial designers. Especially, they extracted eight categories of designer's intention: to elicit specific psychological and behavioral responses from consumers on the visual of product. They were to draw *attention* to the product; to foster *recognition* of product type; to generate *attraction* or desire; to support *comprehension* of function; to encourage *attribution* of qualities; to promote *personal identification*; to stimulate *emotion*; and to provoke *action*. They concluded that designers intend to elicit emotional response in consumers by designing products that will surprise, satisfy, or delight **(Crilly et al., 2009, p.232)**.

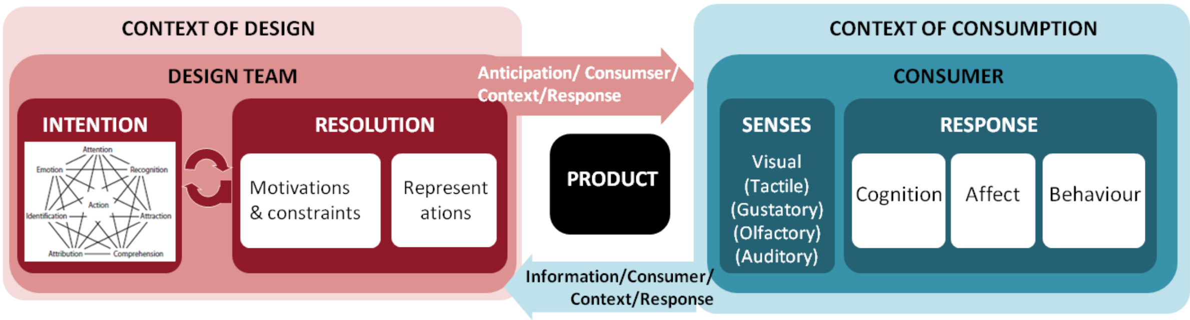


Figure 31. Conceptual framework for product form representing designer intent and consumer response (Crilly et al, 2004, 2009)

In summary, the three models presented above: those of **Helander & Khalid (2006), Ho & Siu (2009), Crilly et al. (2004, 2009)** are of great importance because they explicitly develop theoretical models, which describe the use of emotion from designer's point of view. Up to date, however, there has been no study, at the best of our knowledge, that investigate the side of the role of emotion from designer's perspectives with empirical studies in design.

2.2.2 Emotional aspects of design during cognitive processes

This section describes the role of emotional impact on designer's cognitive process in the early stages of design. After a short review based on the literature review of theoretical/ experimental studies from psychology science and neuroscience, we propose a two-way emotional impact that seems important to understand in this thesis (See Table 3).

'Emotional impact as a generative way' plays a role to regulate mental information process: activating the necessary information or changing attention to match a demanding task. In contrast, 'Emotional impact as an evaluative way' appears when designers employ their own emotions for evaluating or judging their ideas or even designers themselves. Both ways have a strong relation and influence on each during cognitive processes in the early stage of design.

Table 3. A two-way emotional impact on designer's cognitive process (Kim et al., 2010c)

Generative way		
(G1) Aesthetic dimensions entailed harmony rules	Activating the necessary information crossing the different levels of attributes, such as semantic description, shape and color, etc.	Bouchard et al., 2009
(G2) Freshness of the design solutions	Regulating an attention to match demanding task by 'affective feedback'	Barrett et al., 2007 Clore & Huntsinger, 2007 Isen, 1999 Ochsner & Gross, 2005
Evaluative way		
(E1) Intrinsic consistency of the solutions	Evaluating the concept by the entailed harmony rules of information	Bouchard et al.,2008; 2009 Clore & Huntsinger, 2007;2009
(E2) Hedonicity of evaluative judgment	Evaluating the concept by hedonic quality, e.g. designer's satisfaction	Cabanac & Bonniot-Cabanac, 2007 Isen, 1999 Russell et al., 2003

2.2.2.1 Emotional impact as a generative way

- ***Aesthetic dimensions entailed harmony rules (G1)***

Designer's expertise refers to particular knowledge, which is called emotional design in Europe, and more Kansei Engineering in Asia **(Bouchard et al., 2009)**. Design information consists of different levels: high-level (values, semantic words, analogy, and style), middle-level (sector name, context, and function), and low-level information (color, form, and texture). These levels of information can be seen as the position of an axis going from abstract (high-level information) to concrete (low-level information). Especially Kansei is a subjective process, which enables to link high-level information with low-level information. Table 4 shows some examples of Kansei Dictionary (Kansei rules) developed by **Bouchard et al. (2009)** in the field of Image retrieval.

Table 4. Kansei Dictionary (Bouchard et al., 2009)

Most used adjectives for image retrieval by designers	*Related words (synonyms and related words)*	**Impacted low-level features**
Balanced	Stable	Shape : symmetry
Beautiful	Aesthetic, gorgeous	Shape: use of formal harmonies Colour: use of chromatic harmonies
Bright	Brilliant	Texture: reflectance
Classic	Traditional	
Clear	Clean, pure	Colors: white, light greys
Cold	Fresh, freezing, aqua	Colors: cold colors
Dark		Colors: dark colors
Dynamic	Active	Shape: dissymmetry, tense lines
Elegant	Refined	
Exciting	Seductive, appealing	Colors: saturated colors
Light		Shape: dimentional ratios Colors: light colours
Original	Fresh Bizarre Funny	Shape, color and texture: Formal distance to the reference archetype
Motionless		Shape : symmetry
Natural	Simple Authentic	Colors: natural colors (green, …)
Quality	Clean	Texture: finishing, coating with visual and tactile effects
Relaxed	Comfortable	Shape : curves with big radius of curvature
Romantic	Glamour	Colors: unsaturated colors (pastels)
Simple	Basic, clean	Shape: elemental geometrical volumes Colors: plain colors
Soft	Light	Shape: curves Colours: pastels Texture: smooth matter
Warm		Colors: warm colors (orange, …)

This way of activating the necessary information crossing these different levels of attributes are strongly demanding emotional impact on the cognitive process, that we called here 'aesthetic dimensions entailed harmony rules (G1)' The use of semantic adjectives to link words with images and vice-versa impose a much greater cognitive load than low-level attributes **(Pasman, 2003).** That is to say, designers naturally and intuitively recognized the emotional impact on their cognitive activities in: (1) generating high-level information such as value, semantic words, for example, 'well-being' or 'serenity' which can reflect secondary emotion, and (2) categorizing information to provide design solutions which are characterized by semantic expression following harmony rules crossing the different levels of information, and also between several colors, textures and shapes **(Bouchard et al., 2009)**. Specifically, information categorization is based on the use of attributes from low-levels such as formal, chromatic and textural to high-level descriptors. The high-level descriptors are often semantic adjectives, but other grammatical forms are also possible. For example, when describing a "fork-lift truck", semantic adjectives like effective, robust, quick, etc., but also verbs and nouns (acceleration) can occur **(Schütte & Eklund, 2001)**.

- ***Freshness of the design solutions (G2)***

Clore & Huntsinge (2007) have repeatedly shown that the source of affect would be finding oneself making progress on a task or encountering difficulty rather than induced mood states. This 'affective feedback' would then regulate attention and elicit 'cognitive tuning' to meet task demands. **Isen (1999)** also found that positive affect enables flexible consideration of different aspects of concepts, or alternative cognitive perspectives. This facilitative effect of happy feelings promotes creative or innovative responding and does not extend to routine tasks. Like this, the positive affect could play an important role in enhancing the cognitive processes **(Clore & Huntsinger, 2007, 2009; Isen, 1999).** Similarly, **Ochsner et al. (2005)** emphasized the fact that cognitive change might be used, either to generate an emotional response when none was ongoing, or to regulate an already triggered response. Furthermore, according to the psychological point of view on language for the emotion perception **(Barrett et al., 2007)**, it is also possible that emotional words themselves could influence or reactive at a certain stage of stimulus categorization, where memory-based knowledge is being brought to bear on an already formed concept and prior experience. In the field of Kansei, **Schütte (2005)** and references therein emphasize that subjective values like affection, feelings, emotion, and intuition are built up; they in turn led to trigger human creativity (See Figure 32).

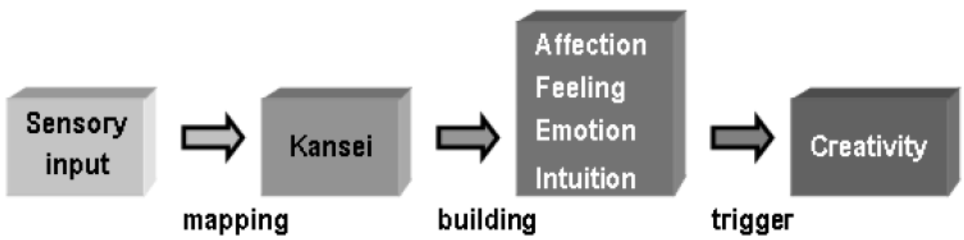


Figure 32. Model of the Kansei (Schütte, 2005, refined model of Lee et al. (2002))

2.2.2.2 Emotional impact as an evaluative way

- ***Intrinsic consistency of the solutions (E1)***

According to **Clore & Huntsinger (2007, 2009),** in performance situations affect provided compelling information about the personal value of whatever is in mind at time and serves as feedback about progress toward goals (Affect-as-information); however, sometimes maximizing positive effect is itself the goal (Affect-as-goal). In this part, the former refers to intrinsic consistency of the solutions, and the latter serves as criteria of evaluation, namely in a hedonic way. Actually, in many design circumstances, informational and hedonic goals often coincide so that it is hard to be conceived separately. As we discussed in section 2.2.2.1 (G1), design information consists of different levels of information (High, Middle, and low). The consistency takes place between all dimensions: high-level (semantics, values) and low-level dimensions **(Bouchard et al., 2007, 2009)**, and also inside low-level dimensions which are related in different directions among and between forms, colors or textures **(Bouchard et al., 2007, 2009)**. Designers made an evaluative judgment of low-level information by high-level information, or also made a judgment or evaluation among the same low-level information.

- ***Hedonicity of evaluative judgment (E2)***

Hedonicity of evaluative judgment is that maximizing positive affect is the goal itself (Affect-as-goal). That is to say, when designers make an evaluative judgment, they often ask themselves about how they do like their idea/sketches. Sometimes it could appear from aesthetic satisfaction, or also accomplishment of assigned design task **(Cabanac & Bonniot-Cabanac, 2007)**. In addition, based on the classification of emotional adjectives in linguistic: stative, manifestive and causative interpretation, when we said that something is ‘interesting’, the meaning of ‘interesting’ does not see a simple value on a scale; however, it can be decomposed in a complex structure such as ‘that stimulates in someone an interest’, or ‘that cause in someone a state of being interested’, etc. **(Goy, 2000)**. Hedonicity, in a sense of positive mode, is useful for making a decision easier and improving quality of these decision **(Isen, 1999)**; however, it could also mislead the point of view between what designer like and what costumer want in the later process. Nonetheless, hedonic value seems to be a very crucial part for understanding designer’s activity in design practice.

2.2.3 Emotional responses to early representations

2.2.3.1 Role of emotional and semantic responses elicited in product form

Designers intend to use their emotions during the design process (See Figure 33). They expect that their design intentions elicit specific psychological and behavioral responses from consumers **(Crilly et al., 2008).** Especially, during the early stages of design, designers try to respond to a given design brief, and find a good form. It is because product form plays a critical role as a precursor to consumers' cognitive and affective responses to a product **(Bloch, 1995)**.

Figure 33. Designer intent and consumer response to product (Crilly et al. 2008)

For example, **Kang and Yamanaka (2009)** have defined nine categories for a favorite cellular phone, and they were: whole form, partial form, color, material, display screen, button, addition function, sound and speaker, and others. As shown in Figure 34, both the designer group and non-designer group took account of 'whole form' features as the most important criteria of a favorite cellular phone. The design field group paid special attention to the shape and structure of product. Moreover, the design field group was more sensitive and discriminated according to product form than rather than to the user.

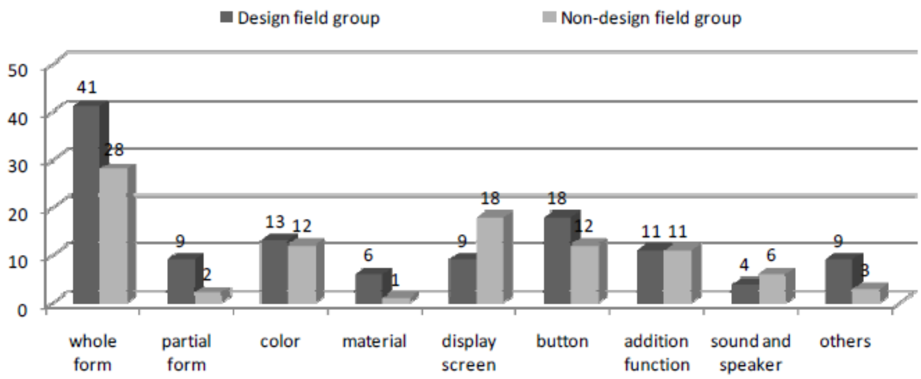


Figure 34. Result of summarized criteria of a favorite cellular phone (Kang & Yamanaka, 2009)

Moreover, according to the comparative study between sketching and modeling condition, **Acuna & Sosa (2010)** found that sketching is a suitable representation aid for the originality aspect of creativity, whilst concrete prototypes are more suitable for the functionality aspect of creativity (see Figure 35). That is, early sketches (product form) can be considered as representations, which can express their original ideas.

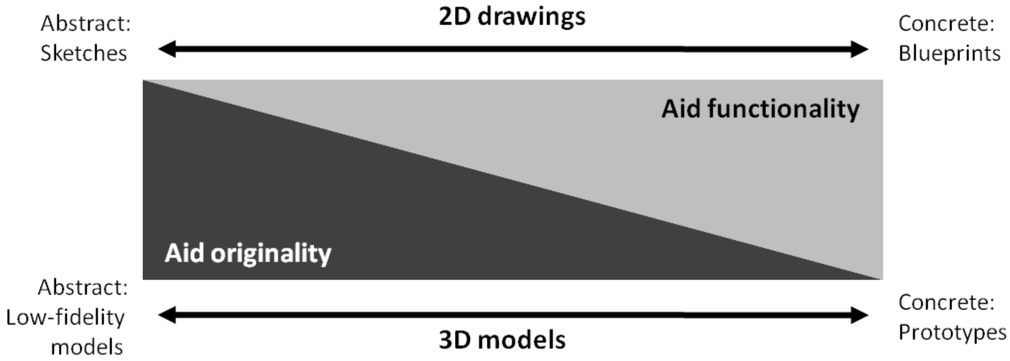
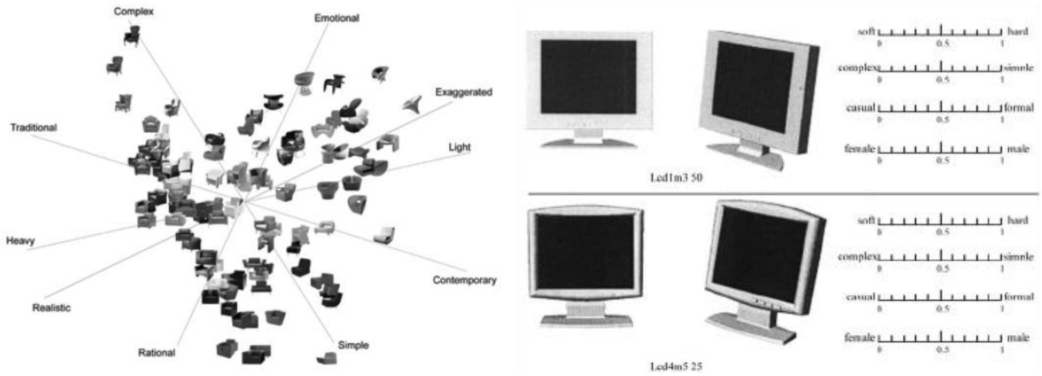


Figure 35. Design creativity representations (Acuna & Sosa, 2010)

In summary, product form plays an important role in defining and imagining final products from the early stages of design. Designers integrate their intent from early representations to the final product. However, in reality, consumer can only meet final products, which brings together various product attributes, including, form, color, texture, brand name, context, etc. Thus, it is hard to recognize whether product form can convey designer's intent and consumers can anticipate their responses to product form.

2.2.3.2 Some pioneers in exploring emotional and semantic responses to product form.

Research toward exploring the semantic and emotional response to the product form has been extensively made in design community and artificial intelligence field. Several studies have been pioneered to identify semantic and emotional response to the pure form feature by eliminating color feature of product in order to set the participant's attention focuses on the form. For example, as Figure 36a shows, **Chuang & Chen (2009)** selected 100 armchairs as stimuli and categorized armchairs form. They employed a semantic evaluation with nine degrees of five bipolar adjectives: Traditional-Contemporary, Rational-Emotional, Complex-Simple, Heavy – Light, Exaggerate-Realistic. **Hsiao & Liu (2002)** were more oriented in numerical shape generation by using 'semantic difference (SD)', such as soft-hard, complexes – simple, casual-formal, and female-male (See Figure 36b). There applications are varied and evolved from automotive design **(Hsiao & Wang, 1999)**, LCD monitor **(Hsiao & Liu, 2002)**, armchairs **(Hsiao & Huang, 2002)**, door lock **(Hsiao & Tsai, 2004)**; coffee maker **(Hsiao, Chiu, & Liu, 2010)**, and so on.



(a) *(b)*

Figure 36. (a) Perceptual map of 100 armchairs (Chuang and Chen, 2009); (b) a questionnaire used to generate the relationships between product forms and their images (Hsiao & Liu, 2002).

More recently, **Lesot et al. (2010)** carried out experimentation with perfume bottles in order to identify a link between shape features and semantic and emotional descriptors. Fifty perfume bottles were annotated with the list of 40 semantic and emotional descriptors; then they employed cluster analysis in order to generate new forms by using significant adjectives (See Figure 37).

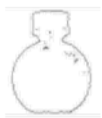
Cluster shape	Significant presence	Significant absence
	Ethereal, tangy, dynamic, mysterious, young, sport	Powerful, attractive, extravagant, aggressive, high-tech
	Playful, warm, sensual	Sport, ethereal, high-tech, austere, masculine

Figure 37. Characteristic adjective presence or absence for cluster shape prototype (Lesot et al., 2010)

In summary, the growing interest in the field of computer-aided design accelerate a link between product forms and semantic/emotional terms. However, those studies are still limited to concrete representations, including shaded, rendered 2D, and 3D numerical prototypes. It cannot sufficiently reflect early representations (sketches) and semantic/emotional terms generated by designers in the early stages of design process. Moreover, several studies have conducted an evaluation of early sketches in terms of creativity (**Bonnardel & Marmèche, 2005)**; however, there has been no study, at the best of our knowledge, that investigates the relationship between early sketches and emotional response.

2.2.4 Synthesis: insufficient consideration on emotional impact during cognitive processes and on early representations (sketches)

In section 2.2, we described emotional aspects of design during cognitive processes in the generative phase and its emotional impact on 'early representations (sketches)'. Our literature review addresses two issues to be further investigated in this thesis.

- **Insufficient consideration on affective processes of designers in conjunction with their cognitive processes**

The Interplay of cognition and emotion is an emerging subject. Even though many cognitive psychology and design researchers have pointed out possible emotional impact during cognitive processes from a theoretical viewpoint, no empirical studies have been conducted to date. Especially research into the affective processes of designer is strongly related to the emotional dimension of early representations. Because these affective processes provide clues to better understand how designers are able to put emotions in their design solutions, and how these solutions are perceived by the consumers.

The key contributions of section 2.2.2 were to present a two-way emotional impact on designer's cognitive process: *generative/evaluative.* This two-way impact has a strong relation and influences each other during cognitive processes in the early stage of design. Further study is necessary to give more empirical evidences to support them.

- **Insufficient consideration on emotional response to early representations**

Designers start with their mental representations in the early stages of design; their early sketches are the first externalized mental representations. Thus, for our purpose, emotional response to early sketches is of great interest. We expect that early sketches may convey emotional values. Given that there are a possible semantic and emotional link to product form at a certain level of abstraction in section 2.2.3.2, it should be emphasized whether emotional response of consumers and designer's intent can meet from early representations. Up to date, however, there has been no study, at the best of our knowledge, that investigate the emotions that early sketches elicited. This is what our thesis aims to address.

2.3 Measuring designer's activity from cognitive to physiological methods

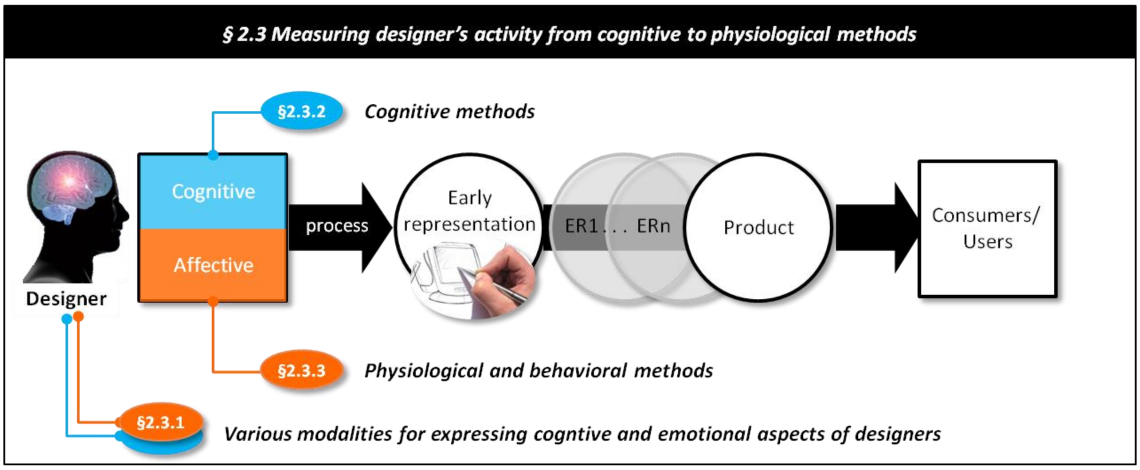


Figure 38. Structure of the section 2.3

A review of methods to measure designer's activity from cognitive and physiological methods is provided in this section. The first two sections focuses on 'cognitive methods' (→§2.3.2) and 'physiological and behavioral methods' (→§2.3.3), and their advantages and drawbacks are also explained. Next, we raise a question about possible combinations of cognitive and physiological methods to identify cognitive and emotional aspects of design in section 2.3.4 (See Figure 38).

2.3.1 Various modalities for expressing cognitive and emotional aspects of design

Since the study on designer's cognitive activity has been of great interdisciplinary interest, Various methods and techniques from psychology, kansei engineering, neuroscience, etc. have been employed in design research. Figure 39 illustrates the main applied methods from the different disciplines on three axes: (1) the X axis represents a range of modality from linguistic expressions to non- linguistic ones; (2) the right Y axis defines the necessary effort for handling instrument during experiment (Light–Heavy); and (3) the left Y axis represents the application domains where a method can be employed by a specific or several domain(s) (specific–versatile). The modalities for expressing cognitive and emotional aspects of design vary within linguistic levels (verbalized words: mental image, semantic words, etc.), behavioral levels (vocal characteristics, facial behaviors, whole body behaviors (hand movement, gesture, posture)), and physiological levels.

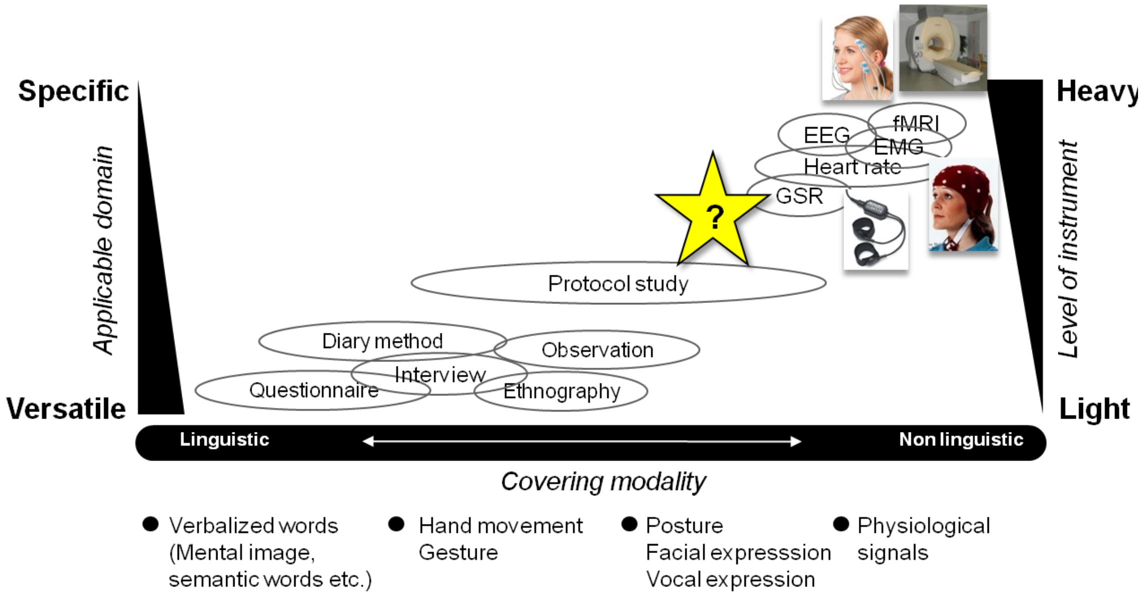


Figure 39. Main applied methods for measuring designer's activity

However, given that emotional aspects of design are hard to be expressed in a lexical way, it is therefore necessary to investigate more subtle modalities for expressing cognitive and emotional aspects of design. Behavioral studies have earlier discovered that body postures and facial movements may be considered as an important affective communication channel **(Dawin, 1965; Ekman &Freitas, 1967; Wallbott, 1998; Desmet, 2002; Coulson, 2004, Bianchi-Berthouze, 2008)**. In addition, vocal outbursts such as laughs, cries, sighs, yawns, etc. seem at first to be good examples of emotional expressions. For example, a funny joke elicits amusement, which produces a laugh; a loss elicits sadness, which produces crying, etc. **(Russell et al., 2003; Ludden, 2008)**.

More recently, the use of physiological signals toward identifying emotions has been pioneered by **Tomino et al. (2008), Jenkins et al., (2009).** In Europe, an intensive research toward developing cognitive methods, including questionnaires, interviews, observations, ethnography, and protocol studies, has remarkably being done **(Cross et al., 1996; Nagamachi, 2001; Coley et al., 2007)**. Relatively, in Asia, psycho-physiological methods are emerging within the scope of Kansei engineering, by combining physiological techniques, such as electromyography (EMG), heart rate, electroencephalography (EEG), etc. **(Nagamachi, 2001; Schütte, 2002; Lévi et al., 2007; Tomino et al., 2008)**.

2.3.2 Cognitive methods

A comprehensive and varied research method is required for understanding information and activities related to design **(Cross et al., 1996)**. In many cases, these methods have been based on the explicit representations used or produced by designers; therefore, they have certain limitations insofar as many of the cognitive activities of designers during the early stages of the design process are implicit. One approach to this issue is provided by methods drawn from ethnography **(Blomberg et al., 1993; Buciarelli, 1994; Lawson, 1990; Cross et al., 1996; Lindlof and Taylor, 2002)**. Data collected using an ethnographic methodology often derives from observations, interviews, and questionnaires completed in real contexts rather than from results of laboratory experiments. Another approach to this issue is provided by the think-aloud method, which is based on observations and verbalizations **(Akin, 1976; Cross et al., 1996; Suwa & Tversky, 1997; Eastman, 2001; Bilda & Gero, 2007; Coley et al., 2007)**. A summary of data collection tools capturing design activities is provided in Table 5.

Table 5. Summary of data collection tools for capturing own design activity (an excerpt from the work of Pedgely (2007))

Data Collection Tool	***Brief description***
Project archiving	Designer systematically collects and archives outputs of modeling, minutes of meetings and suchlike
Project report	Varied and detailed factual account of project by designer, created at project end
Interview	Spoken exchanges between designer (interviewee) and researcher (interviewer)
Questionnaire	Printed document prepared by researcher, completed by designer, ranging from 'tick box' to 'write about' requests
Survey	Variation of interviews and questionnaires administered on large scale to gain statistically strong generalized results
Observation	Researcher (observer) takes notes on designer's (participant's) externally perceptible activities
Participant observation	Designer observes and takes notes on dynamics of social situations including own behavior and activities
Action research	Extension of participant observation: designer initiates/evaluates effects of planned intervention on social situation
Diary	Reportage on designing given at regular intervals with emphasis on personal experiences and perceptions
Protocol analysis	Real-time audio (concurrent verbalization) and visual (video recorded) 'protocols' to reveal cognitive activity
Replication protocol analysis	Researcher (replicator) deduces designer's apparent line of thinking given only design brief and final proposal
Reflective conversation	Variation of interview in which designer uses reflection in/on action to verbalize thinking during/after design episodes

2.3.2.1 Ethnographic approach

Ethnographic approach is originated from anthropological and sociological research. Ethnography requires a period of fieldwork where the ethnographer becomes immersed in the activities of the people in the study **(Blomberg et al., 1993)**.

- **Interviews with designers: Cross, N. (2008, p. 50)** described that ''Interviews with designers have usually been with designers who are acknowledged as having well developed design ability''. Interviews could be in various forms, such as structured/unstructured, directed/non-directed, or individual/group ones **(Lawson, 1994; Cross & Clayburn Cross, 1996)**. In design cognition, it is recommended to use more unstructured or semi-directive interviews in order to assess mental processes of designers. According to the instrument of semi-directive interviews developed by **Lindlof and Taylor (2002)**, the interviewer provides various questions in order to obtain the responses in repeating broad and open ended questions until the interviewer could gather the valuable answers, for example, 'what did you think when you received the design brief?', 'tell me more about your thinking on that', or 'what is that?', etc.

- **Case studies:** *''These have usually been focused on one particular design project at a time, with observers recording the process and development of the project either contemporaneously or post-hoc''* **(Cross, 2008; p. 50)**. Records of the process might be with participant or non-participant observation. Case studies in longitudinal context may bring an in-depth understanding of community, a wealth of information, and a rich description through an intense interaction and observation **(Coley et al., 2009)**. However, this method is still limited in application because of the low feasibility and cost-effectiveness **(Ball & Ormerod, 2000)**.

- **Diary method:** The diaries are also one of the widely used methods in social science and psychological research to gather ethnographic data (See Figure 40). Participants are asked to write their thoughts and feelings in a diary with the aim of gaining an insight into their cognitive thoughts **(Coolican, 1990; Coley et al, 2009)**. Recently, **Pedgely (1999, 2007)** investigated a diary method to capture design activities in the longitudinal studies. He suggested that a diary method is an effective way for data collection in longitudinal context. It did not influence natural design processes. However, the diary method is still limited in application for the following reasons: (1) High and unchecked observer's bias **(Coolican,**

1999), (2) Low feasibilities to maintain the long-term study, especially with professionals **(Pedgely, 1999, 2007)**, and (3) Difficulties of controlling diary submission and formatting **(Webb, 2005)**.

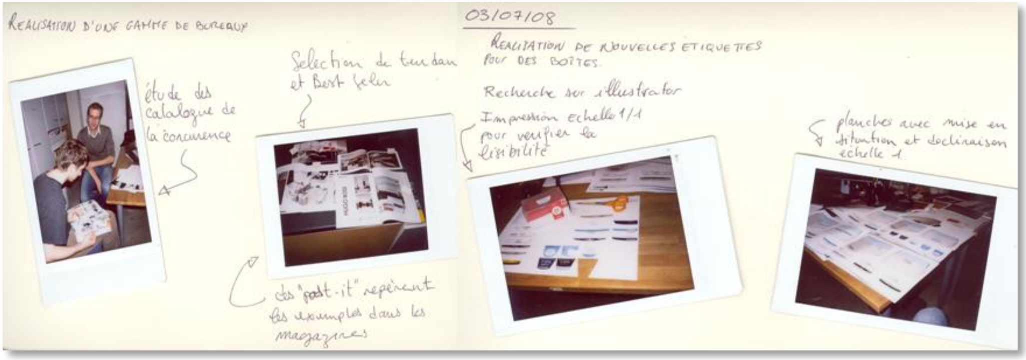


Figure 40. Examples of diary method

2.3.2.2 Protocol Studies

In design research, verbalization and its subsequently protocol analysis have become the most experimental technique used in design research for capturing, understanding, and analyzing of design thinking **(Akin & Lin, 1996; Cross, 1996; Suwa & Tversky, 1997; Suwa et al., 1998; Gero & Tang, 2001; Bilda, 2006; Coley et al., 2007; Cross, 2008)**. Protocol analysis is a research methodology based on the psychological theory of information processing. Usually, 'Think-aloud (Verbalization) and associated actions of subjects are asked to perform a set of design task.

Given that the early stages of design are considered to be among the most cognitively intensive in the design process **(Nakakoji, 2005)**, several studies based on interior and architectural designs have been pioneered toward understanding the sketching activities of designers during the generative phase **(Schön & Wiggins, 1992; Goldschmidt, 1994; Suwa & Tversky, 1997; Bilda & Gero, 2007)**. Since the beginning of the 1990s, a few studies dedicated to the sketching activity of designers have emerged in mechanical engineering design; these include **Ullman et al., (1990), Goel (1995), Purcell (1998), Yang (2009)**. Table 6 is a summary chart of protocol studies with designers: excerpt from the work of **Cross (1997)**.

Table 6. Summary chart – Protocol and Other Formal Studies of Design Activity (Cross, 1997)

YEAR	Architecture	Industrial design	Mechanical engineering	Electronic engineering	Software design	Various /Others
1970	Eastman					
1973	Foz					
1978	Akin					
1979	Lawson					Thomas
1981					Jeffries	
1983	Schön					
1985					Adelson	
1987		Ballay	Stauffer			
1988	Eckersly		Ullman			
1989			Radcliffe			
1990	Chan		Tang, Visser		Guindon	
1991	Goldschmidt		Jansson	Colgan		
1992		Christianns	Purcell		Davies	Goel
1993			Fricke		Olson	
1994			Lloyd	Ball		
1995		Dorst				
1997	Suwa					Göker
1998		Valkenburg		McNeil		Smith
1999			Atman			

Generally two types of think-aloud methods have been used: concurrent and retrospective. During the concurrent verbalizations, designers were instructed to design and simultaneously think aloud. The concurrent protocol could point out detail sequences of information process reflecting the designer's working memory (WM); therefore it has been utilized to reveal the process-oriented aspects of designing **(Ericsson & Simon, 1993; Dorst & Dijkhuis, 1995; Gero & Tang, 2001)**. Whereas skeptical researchers claimed that concurrent protocols hinders the nature of design process and causes incompleteness in revealing the design process **(Davices, 1995)**. Comparatively, the retrospective protocol has been used in experiments which focus on the cognitive content aspect because it could retrieve the trace of the cognitive process and reveal information partially in both working memory (WM) and long-term memory (LTM) **(Dorst & Dijkhuis, 1995; Gero & Tang 2001)**. However, this retrospective way may also provide insufficient and reinterpreted information due to the decay of LTM **(Bilda & Gero, 2007, Cross et al., 1996; Davices, 1995, Ericsson & Simon, 1993; Lloyd et al., 1995)**. More recently, **Gero & Tang (2001)** showed that concurrent and retrospective verbalization have very similar outcome in case of the process-oriented aspects of designing. However, the debates on the validity of think-aloud protocols are ongoing; researchers should choose one or other methodology depending on their goals.

2.3.3 Physiological and behavioral methods

2.3.3.1 Overview of existing measuring methods

There has been a long history of researchers measuring physiological signals to try to identify cognitive and emotional state. Physiological signals can be assessed from three different physiological sources: (1) the central nervous system, which corresponds to the brain activity, (2) the cardiovascular system, which concerns the organs that regulate blood flow, and (3) the peripheral system, which also involves the expressions coming from the motor system. Specific measuring methods and techniques are necessary to assess each human system. Figure 41 illustrates a selection of physiological methods corresponding to the human system.

- **Central nervous system:** Functional Magnetic Resonance Imaging (fMRI), and Electroencephalograms (EEGs);
- **Cardiovascular system:** Heart beat, Blood pressure, Blood oxygenation, Respiration rate, and Electrocardiogram (ECG);
- **Peripheral system (+motor system):** Electrodermal activity (EDA), Body temperature, Eye position tracking, Pupillometric, Electrooculography (EOG), and Electromyography (EMG).

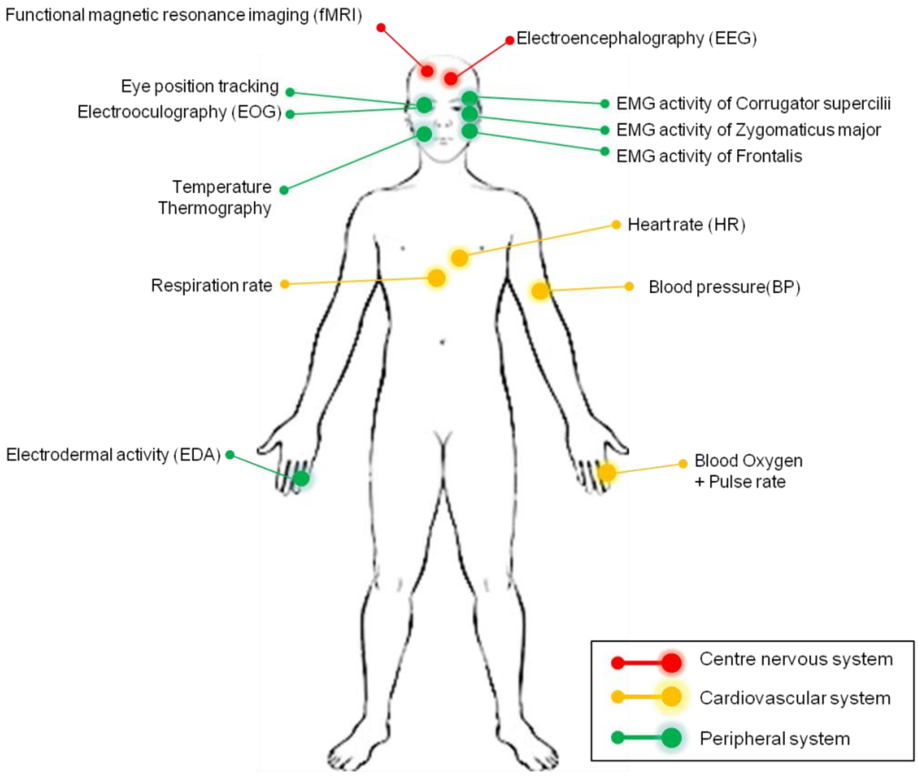


Figure 41. Position of various physiological signals

Figure 42 illustrates the most popular used physiological measurements in design research: Electroencephalogram (EEG), Electrodermal Activity (EDA), Electrocardiography (ECG), Electromyography (EMG), and Eye tracking system.

(a)	(b)	(c)	(d)	(e)
EEG (g.Mobilab)	EDA (Biopac)	ECG (Healthwatch)	EMG (g.Mobilab)	Eye tracking (SMI)

Figure 42. Examples of physiological measurements

Electroencephalogram (EEG) records the electrical sum activity of the neural structures in brain with surface electrodes at the skin **(FEEL EUROP, 2008)**. Particularly, early studies of frontal asymmetry found a strong link to emotional valence. However, EEG has not widely employed due to the complexity of instrument (See Figure 42a). **Electrodermal Activity (EDA, also known as galvanic skin response, or GSR)** is a very popular measurement in physiology and Human computer interaction (HCI). It measures the changes of skin conductivity, which indicates an effective correlation to arousal. Significant advantages of EDA are that (1) it is easy to handle, and cheap; (2) it provides continuous information; (3) it is highly sensitive to arousal **(Tran et al., 2007; Ganglbauer et al., 2009)**. However, EDA is subject to experiment environment, including a room temperature, humidity, etc. (See Figure 42b). **Electrocardiography (ECG)** measures the heart rate, including RR-interval duration, heart rate variability, etc. **(SEAT Project D1.1, 2006)**. ECG has been used to determine the emotional state (arousal and valence) and mental state (e.g. cognitive workload and attention). ECG is often combined with body temperature and en electrodermal activity (EDA) (See Figure 42c). **Electromyography (EMG)** measures muscle activities by detecting surface voltages that occur when a muscle is contracted **(Ganglbauer et al., 2009)**. Facial EMG has a strong correlation to emotional valence (See Figure 42d). **Eye tracking system** can provide both cognitive and physiological data. Traditionally, eye-tracking system is used for the former, such as gaze position, fixation number, fixation duration, repeat fixations, search patterns, etc. Recently, the latter, physiological pupillometric data is also of great interest **(Ganglbauer et al., 2009)** (See Figure 42e).

More detailed information of physiological methods and their advantages/disadvantages are described in Table 7.

Table 7. Summary of existing physiological measures (not exhaustive) (SEAT Project D1.1, 2006; Tran et al., 2007; FEEL EUROP, 2008; Ganglbauer et al., 2009)

	Physiological measures	Advantages	Disadvantages
Central nervous system	**Functional Magnetic Resonance Imaging (fMRI)**	Sensitive to vigilance, workload, and valence; high spatial solution; visualizing activated brain areas regarding to brain activity.	Low time resolution (25 minutes for a complete scan of a head), requiring a separated room with the measurement set-up.
	Electroencephalograms (EEGs)	A good time resolution (ms.), visualizing the activity of different brain area.	High complexity of instrument
Cardiovascular system	**Heart rate**	Sensitive to arousal, valence, mental workload, and attention; Providing continuos information.	Slow rising and declining relative to the trigger event; privacy and intimacy issues (the attachment of electrodes in the chest area)
	Blood pressure and oxygen	Sensitive to stress, difficulty of cognitive tasks, and emotional intensity; inexpensive commercially available device; non-invasive measurement.	Susceptible too many factors to be a reliable measures.
	Respiration rate	Sensitive to negative valence and arousal; simple and reliable measurement.	Respiration rate affects other psycho physiological metrics, such as EDA or cardiovascular functions.
Peripheral system (+Motor system)	**Electrodermal activity (EDA)**	Sensitive to arousal; providing continuos information.	Subject to room temperature, humidity, participants activities, etc.
	Temperature thermograph	Sensitive to negative affect and relaxation; providing continuous information.	Contact less, very slow rising and declining.
	Eye position tracking	Able to determine several cognitive states during task.	No signal when there are no visual targets.
	Electrooculography (EOG)	Sensitive to fatigue, difficulty, emotion, etc., able to determine several cognitive states during task.	Being affected by sudden changes of image intensity, very obstructive.
	Electromyography (EMG)	Sensitive to valence of emotions (Positive : zygomaticus; Negative : corrugators supercilious), more accurate than facial expression recognition with video analysis, robust.	Very obtrusive due to the electrodes directly placed around the eyes.

2.3.3.2 Advantages and disadvantages in cognitive and physiological approach

A cognitive approach is relatively simple, cheap, and quick measurement. Especially subjective evaluations through questionnaires and interviews are convenient and easy to administer. In addition, they can specify secondary emotions in a lexical way **(Lang, 1997; Nagamachi, 2001; Mantelet, 2006; Bouchard et al., 2007).** However, cognitive evaluations have raised some disadvantages to apply. They are not able to assess in real time, and hard to catch emotional respons objectively or continuously. In addition, the use of emotional scales, which often contains a long list of emotion adjectives, might cause respondent's fatigue. Moreover, some of respondents have difficulties of expressing their feelings because they are not always aware of them, or certain pressure from social bias **(Poels &Dewitte, 2006)**.

In comparison, a physiological approach can give quantitative and objective data in real time **(Tran et al. 2007)**. However, unnatural, obstructive, and heavy instrument might interfere with designer's natural activity and influence the results **(Tran et al. 2007; Ganglbauer et al., 2009)**. Certain physiological measures are unable to be worn for a long duration of time because it may induce the physiological measurement to overheat **(Tran et al. 2007)**. Moreover, uncontrolled environmental setting may rise arousal or cause different emotions. The overall average of data precision is reported only 70-80 %, which is not sufficient **(Ganglbauer et al., 2009)**.

Hence, combining cognitive and physiological measurements may compensate disadvantages of other measurements. However, it should be applied under careful considerations. The following sections provide some examples of a combination of cognitive and physiological measurements (§2.3.3.3) and new physiological sensors to be used in mobile context (§2.3.3.4).

2.3.3.3 Some pioneers in combining cognitive and physiological methods in design field

In design field, some pioneers have started to combine cognitive and physiological methods in order to explore a cognitive and emotional state. This approach is very emerging interdisciplinary issues to collaborate with experts from psychology and neuroscience. For example, **Tomico et al. (2008)** carried out a pilot study in order to explore the suitability of psycho-physiological measures in case of using Zebra pens. They combined 2-point Electroencephalogram (EEG) and Repertory Grid Technique (RGT) interviews in order to measure degree of comfort in terms of pleasantness and arousal (excitement) (see Figure 43).

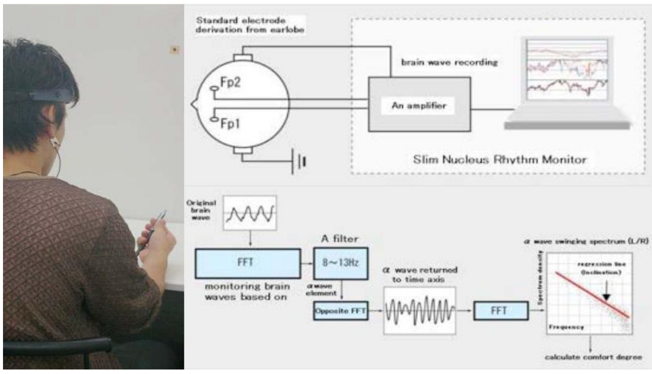


Figure 43. Experimental set-up: EEG (Tomico et al., 2008)

Jeskin, Brown, & Rutterford (2009) conducted a more rigorous experimentation for comparing Infrared Thermography (IRT), Electroencephalogram (EEG), and Subjective measures of Affective Experience (ASR) to measure a cognitive work and affective state. They found that significant correlation between IRT, EEG, and ASR (see Figure 44).

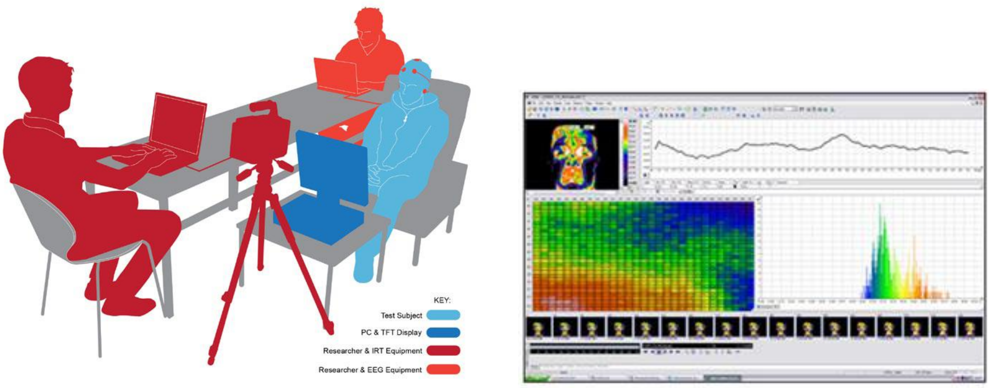


Figure 44. Experimental set-up: EEG+IRT (Jeskin et al., 2009)

2.3.3.4 Challenge toward new physiological sensors in mobile context

Recently, a growing trend is emerging toward the development of wearable, mobile physiological sensors in Human Computer Interaction (HCI). The introduction of new technology in physiological sensors enables us to increase their data precisions and reduce post processes for analysis. Moreover, thanks to a long-term usability and comfort, new physiological sensors could be widely employed in practical applications **(Tran et al. 2007)**. Thus, the emerging research from Kansei Engineering **(Schütte, 2002)** and HCI community could be a good source to prompt this approach, for example, the contents at HUMAINE Portal. Figure 45 shows some examples of new physiological sensors developed in the field of HCI.

Figure 45. Examples of new physiological sensors in HCI

EREC II system (Peter et al., 2007) provides the multi sensors for skin resistances and skin temperature (See Figure 45a). **Communication-wear (Baurley et al., 2007)** is a wearable clothing concept, which includes integrates textile gesture, heatable textile sensor, and Galvanic Skin Response (GSR) (See Figure 45b). **IMEC wireless EEG (IMEC, 2007)** is a wireless headband type of EEG sensors, which monitors brain wave without need of any battery (See Figure 45c). **Aachen Smartchair -ECG (Aleksandrowicz & Leonhardt, 2007)** is a chair concept for Electrocardiography (ECG) measures without a direct skin contact (See Figure 45d). **Armband–EMG (Costanza et al, 2007)** is an electromyography (EMG) based wearable input devices (See Figure 45e). **Mimi Switch (Taniguchi, 2009)** detects facial expressions using infrared sensors embedded on the speaker's earbud (See Figure 45f). **SMI-Eye tracking (SMI, 2009)** is a fully mobile eye tracking system which includes a tablet PC and a lightweight headset (See Figure 45g).

2.3.4 Synthesis: the need to combine cognitive and physiological methods

In section 2.3, we pointed out some advantages and also drawback from cognitive and physiological methods. Note that the physiological methods can give us promising objective results in conjunction with the results from cognitive methods. Moreover, they may detect more subtle emotional and cognitive state of designer's activity. Accordingly, a challenging work is to balance cognitive and physiological method to under careful consideration **(Dorst & Dijkhuis 1995; Coley et al., 2007).** It is necessary to develop new economic and feasible mobile sensing techniques **(Tran et al., 2007)**.

In our context, the study brings together cognitive and affective processes of designers and their early representations (sketches) in the generative phase. First, considering the relationships between cognitive and affective processes of designers, a protocol study should be employed to extract the link between mental information and cognitive operations during early sketching activities. In addition, we also need to combine physiological or behavior method in order to analyze designer's unconscious changes, for example, changes of physiological signals and posture/body movements of designers. Second, regarding the evaluation of emotional response to early representations (sketches), we employed cognitive methods based on a semantic differential approach, which has been mainly studied in emotional design and kansei engineering. In addition, it is necessary to combine physiological methods with cognitive methods in order to assess continuous and objective emotional state. Finally, both cognitive and physiological approaches may enable us to quantify emotional response to early sketches and give promising objective results.

In summary, during our empirical study, we employed both cognitive and physiological methods in order to formalize cognitive and affective processes of designers and identify emotional response to early representations.

2.4 Conclusions of the state of the art

The previous sections provided critical literature reviews on the designer's cognitive activity in the early stages of design (§2.1), interplay of cognition and emotion in design (§2.2), and existing cognitive and physiological methods to measure those implicit aspects of design activity (§2.3).

We found that there is a research gap between the informative and generative phases in the early stages of design, where designers mentally categorize design information in order to further generate early sketches. In this thesis, this specific phase was defined as the phase of ''mental categorization of information processing''. It is necessary to extract mental information and its cognitive operations. In addition, along with a growing interest in hedonic values of product, it is necessary to understand how designers are able to put emotions in their design solutions, and how these solutions are perceived by the consumers. Thus, emotional aspects of design and the possible emotional dimensions of early representations should be taken into account in conjunction with cognitive aspects of design activity. In order to do this, research on the cognitive and physiological methods became a need to identify and quantify subtle emotional response. Finally, we summarized the four major limitations of current research as follows:

L1: The need to formalize a cognitive model, dedicated to mental categorization of information processing in the generative phase;

L2: Insufficient consideration of emotional aspects of design during designer's cognitive process dedicated to our specific phase;

L3: Insufficient consideration of emotion response to early representations (sketches);

L4: The need to combine cognitive and physiological methods.

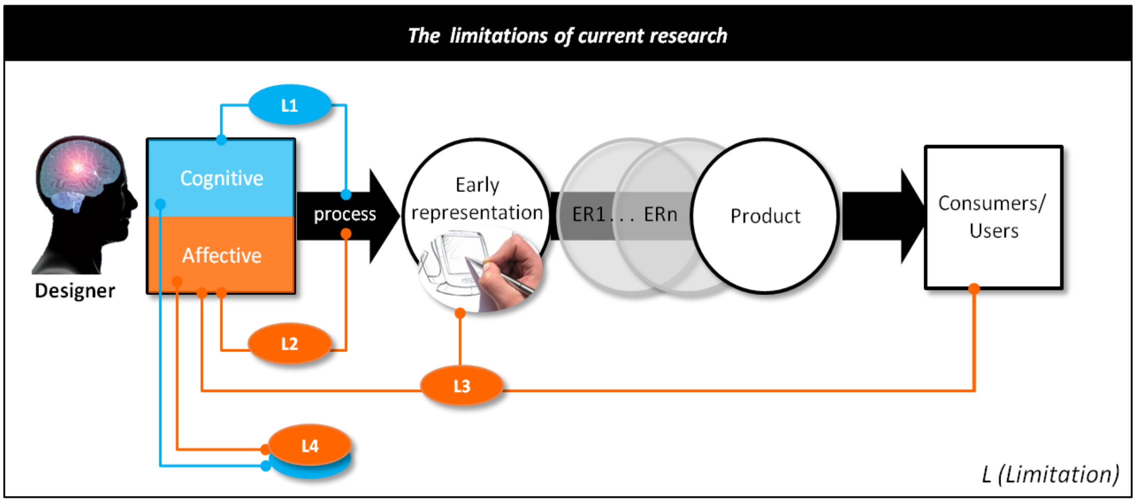


Figure 46. The limitations of current research

III. RESEARCH QUESTION AND HYPOTHESES

Introduction

Chapter III formulates a research question and develops the hypotheses of this thesis. It is based on the state of the art of cognitive and emotional aspects of design as well as the review of cognitive and physiological methods based on relevant design science and psycho-physiology.

The core research question explored in this thesis is about **how the cognitive and affective processes of designers can be modeled, specifically, during the mental categorization of information processing performed in the generative phase**. The generative phase is characterized by the production of sketches to find a ‘‘good form’’ of one or several concept(s).

The following hypotheses are explored:

Hypothesis 1 suggests developing a model of cognitive and affective processes of designers, whereby designers mentally categorize design information;

Hypothesis 2 proposes that emotional reactions to early representations (sketches) should be formalized in order to predict their emotional dimensions.

3.1 Research question

Based on the four major limitations of current research discussed in section 2.4, we raised a research question about **how the cognitive and affective processes of designers can be modeled, specifically, during the mental categorization of information processing performed in the generative phase** (See Figure 47)**.**

Given that early stages of design are considered to be among the most cognitively intensive in the design process, several studies have been progressively investigating these stages in order to formalize and develop an explicit model of these. However, since much design research focuses on the external information and the explicit design processes, there has been a research gap between the informative and earliest generative phases, which are relatively implicit.

We defined this specific gap as the phase of 'mental categorization of information processing' in this thesis. During this phase, designers employ various levels of mental information, and gradually integrate and synthesize them into their memory in order to further generate early sketches. Thus, it is necessary to develop an explicit model wherein designers mentally categorize design information.

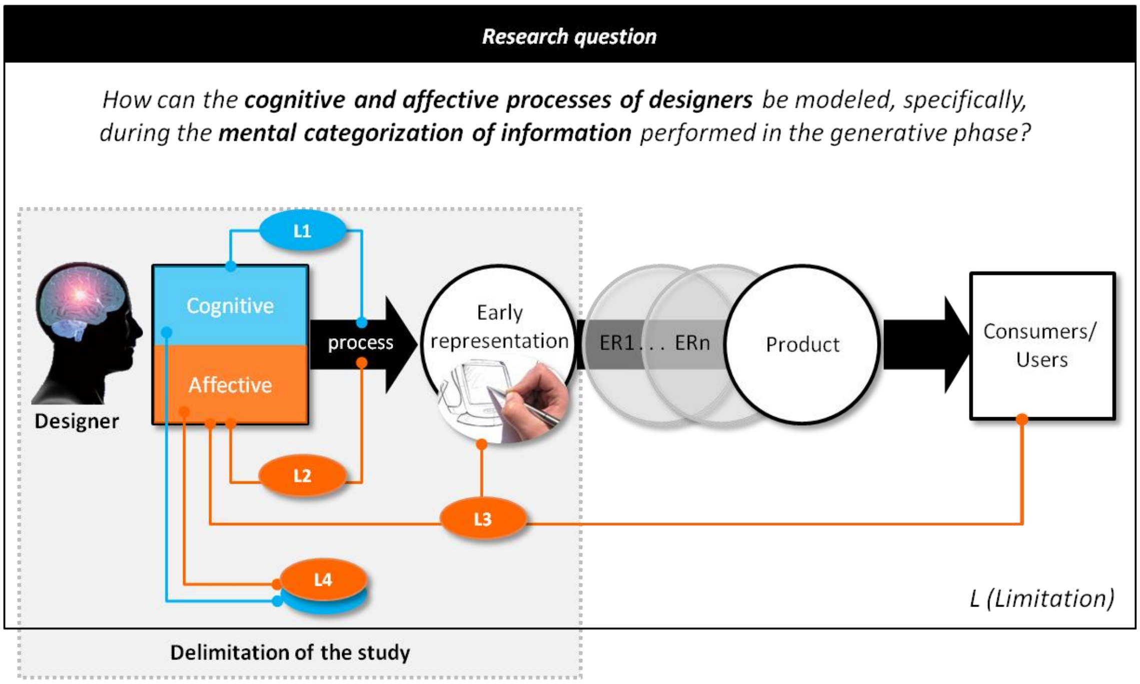


Figure 47. A research question of the study

In addition, as hedonic aspects of product appear to be important dimension of the product, we propose that the study of emotional aspects of design become crucial in order to understand how designers are putting emotions into early representations, and how these emotional dimensions of early representations can be anticipated. Considering that early sketches are the first externalization of these mental representations in the generative phase, we assume that they may contain designer's intent, and can play a role in predicting emotional response of consumers. Hence, in this thesis, we aim to formalize and develop an explicit model of cognitive and affective processes of designers, through understanding designer's mental process and its relationship with early representations (sketches) together. Moreover, to meet the needs from an industrial context, this model would provide system specifications for developing a computational tool dedicated to our specific phase. Finally, it would contribute to digitalize and optimize the whole design process.

3.2 Developing hypotheses

To answer our research question about ***"how can the cognitive and affective processes of designers be modeled, specifically, during the mental categorization of information processing performed in the generative phase?"***, we developed two main hypotheses as follows:

HYP 1: Designers' cognitive and affective processes, whereby designers mentally categorize design information can be modeled.

HYP 2: Emotional response to early representations (sketches) should be formalized in order to predict their emotions from the early stages of design.

Figure 48 summarized the main hypotheses of the study. The detailed sub-hypotheses are explained in the following sections.

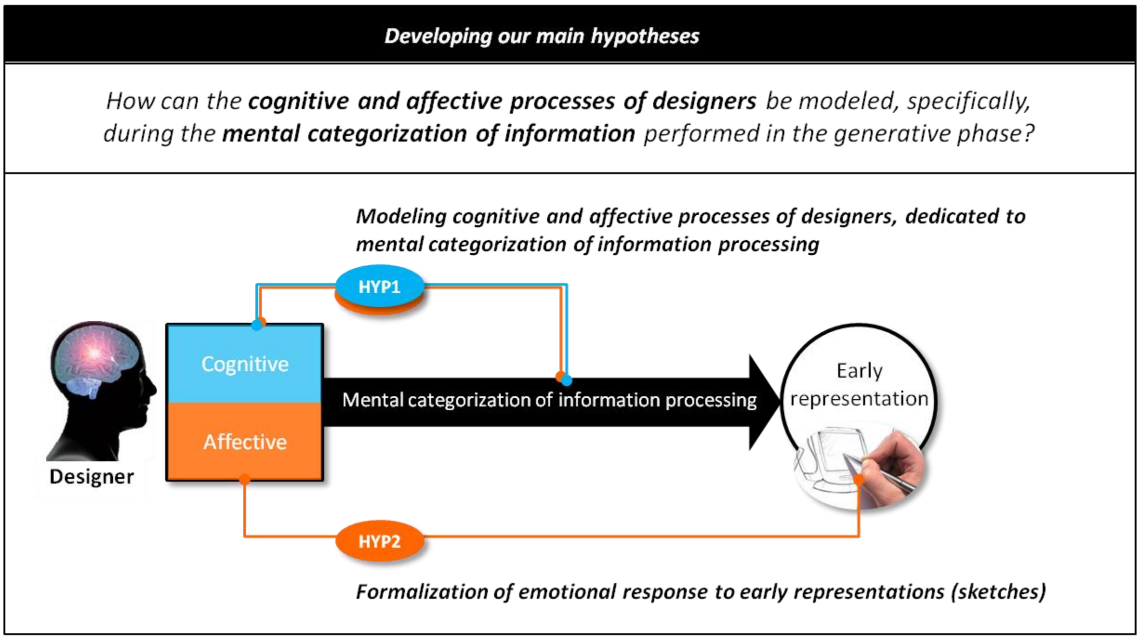


Figure 48. Developing our main hypotheses

3.2.1 HYP 1: Modeling cognitive and affective processes of designers, dedicated to mental categorization of information processing

HYP 1 brings together cognitive and emotional aspects of design and their processing, where designers mentally categorize design information during the generative phase. HYP 1 may be partitioned into a set of sub-hypotheses (HYP 1.1 and HYP 1.2) as summarized in Figure 49.

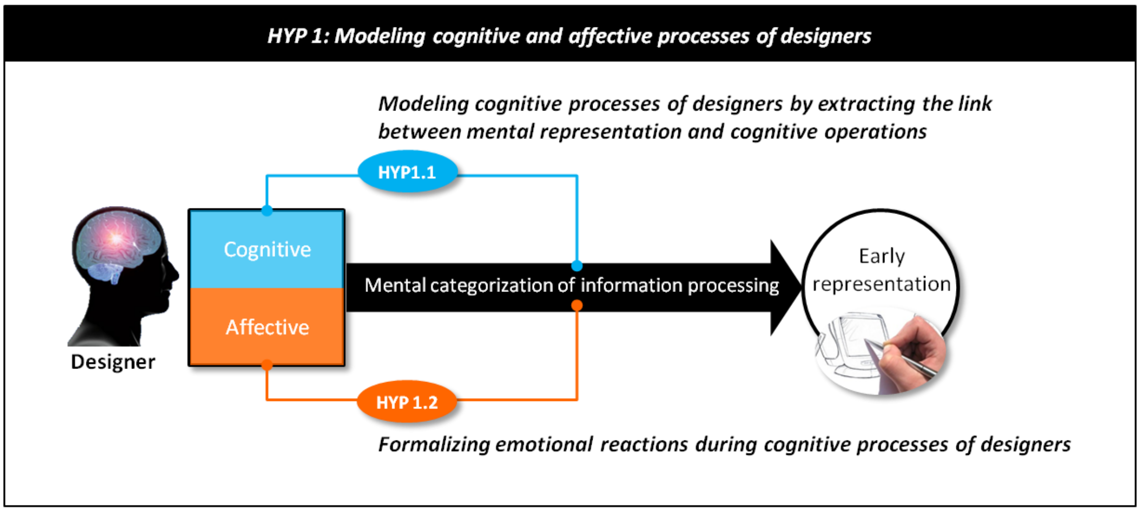


Figure 49. Structure of HYP1

3.2.1.1 HYP 1.1: Modeling the cognitive processes of designers by extracting the link between mental representation and cognitive operations.

HYP 1.1: the cognitive processes of designers during mental categorization of information processing can be modeled. In order to do this, it is necessary to extract mental information from memory and identify a kind of cognitive operation to understand how design information is mentally transformed or categorized during early sketching. Toward this goal, as **Finger & Dixon (1989)** and **Takeda et al. (1990)** pointed out, a descriptive model allows us to clarify and define design activity from a theoretical viewpoint. Further, it can be refined and enriched through empirical studies toward developing a cognitive model.

We developed a descriptive model of information processing that integrates memory models drawn from cognitive psychology: those of **Atkinson and Shiffrin (1968)**, **Baddeley et al. (2009)** (See Figure 50). Integrating memory models was particularly pertinent to our study because there is a similar mechanism of mental categorization of information processing linked to long-term memory (LTM) and working/short-term memory (WM/ STM), as designers do it in practice. Design information consists of different levels. We have defined three of these: high-level (values, semantic words, analogy, and style), middle-level (sector name, context, and function), and low-level information (color, form, and texture). The consistency takes place in crossing different levels of information and also inside the same level of information. For instance, a semantic word (high-level) 'warm' can represent color from the red series (low-level). Similarly, according to the agreed memory theory from cognitive psychology **(Atkinson & Shiffrin, 1968; Collins & Quillian, 1969; Baddeley et al., 2009)**, LTM stored information in an associative network with nodes and links. A node may contain concepts, words, images, or any other information, and a link represents an association between nodes. They also employed a notion of high- and low- level of processing as we observed in design practice. Given that designers employ both internal memory (STM/LTM) and extended memory (sketches) during the earliest generative phase, we propose that a descriptive model based on memory models is crucial and pertinent. This may enable to understand how design information can be categorized in long-term memory through short-term memory and how categorized mental information in long-term memory can then be externalized into the extended memory later on.

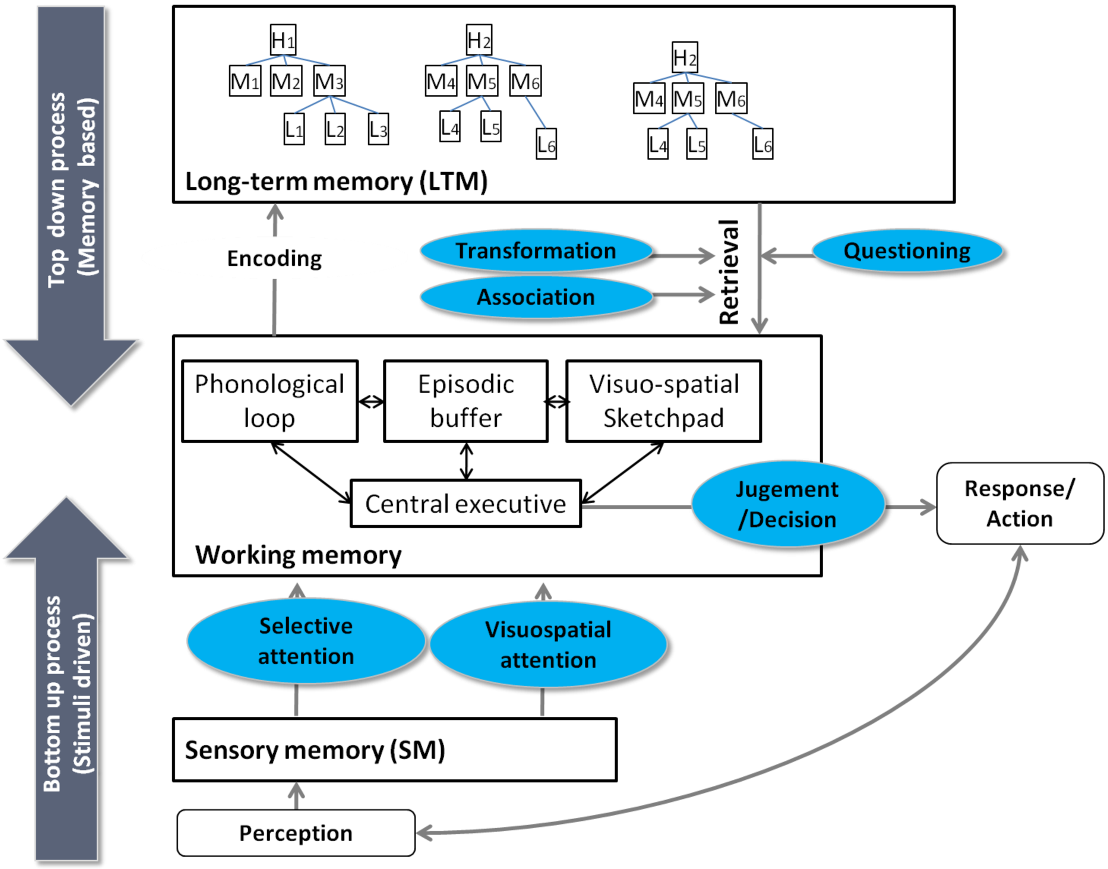


Figure 50. Proposing a descriptive model of Information processing (integration of the multiple components of memory models from Broadbent (1958), Atkinson & Shiffrin (1968), and Baddeley et al. (2009))

According to our descriptive model of information processing in Figure 50, **Broadbent (1958)**, proposed a sequence of cognitive processing stages that can be performed in bottom-up or top-down order. In this thesis, we focus particularly on top-down (i.e. memory-driven) processes. We selected cognitive operations related to six phenomena to account for overall information processing: selective attention, visuospatial attention, questioning, association, transformation, and judgment/decision. In detail, cognitive operations involving questioning, associating, and transforming play roles in retrieving memorized design information from long-term memory (LTM) and moving it to working/short-term memory (WM/ STM). They were based on a Geneplore model defined by **Finke et al. (1992)** in the work of **Benami & Jin (2002)**. The remaining operations (those pertaining to selective attention, visuospatial attention, judgment/decision) were based on the model defined by **Harris (1992), Ball & O'Callaghan (2001),** and **Style (2005).**

During empirical studies, this model was refined and enriched via a protocol study with product designers. These six cognitive operations and three levels of information (high/middle/low) have been used to coding scheme to extract what kind of mental information is extracted and how it can be transformed or categorized through cognitive operations during early sketching.

3.2.1.2 HYP 1.2: Formalizing emotional reactions during cognitive processes of designers

Although investigating cognitive process of designers is of great interest for research and practice (HYP1.1), one should not forget the importance of the emotional aspect of design work. The affective processes of designers may provide clues to better understand how designers are able to put emotions in their design solutions, and how these solutions are further perceived by the consumers.

Based on the literature review related to designer's cognition and emotion especially in the early stages in section 2.2.2, a two-way emotional impact seems important to understand the affective processes of designers, as summarized in Figure 51.

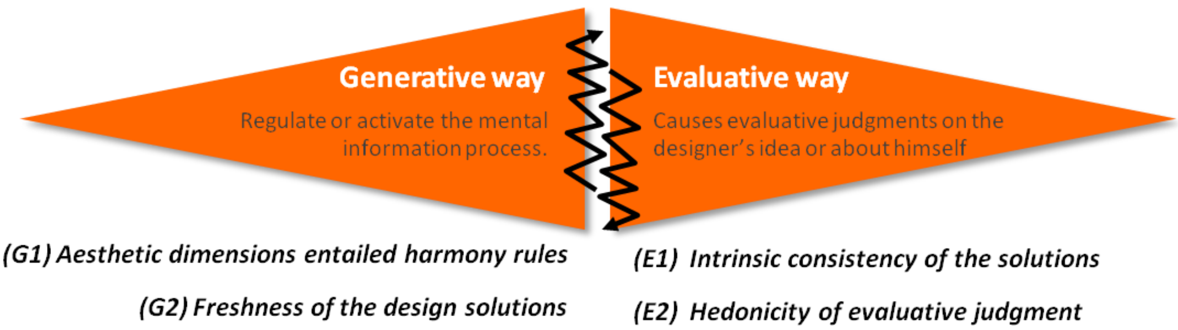


Figure 51. A two-way emotional impact during cognitive processes of designers (Kim et al., 2010c)

'Emotional impact as a generative way' plays a role in regulating mental information process: activating the necessary information (G1: Aesthetic dimensions entailed harmony rules) or changing attention to match a demanding task (G2: Freshness of the design solutions). On the other hand, 'Emotional impact as an evaluative way' is an emotional impact which causes evaluative judgments on the designer's idea (E1: Intrinsic consistency of the solutions) or even about himself (E2: Hedonicity of evaluative judgment). The two-way impact has a strong relation and influence each other during cognitive processes in the early stage of design. Therefore, the above finding from literature leads to the following hypothesis:

HYP 1.2 : Emotional reactions of designers will interplay with the cognitive processes of designers in generating stimuli and evaluating their results during the generative phase.

Further study is necessary to give more empirical results to support the two-way emotional impact, which we hypothesized above.

3.2.2 HYP 2: Formalization of emotional response to early representations (sketches)

While HYP 1 concerns cognitive and emotional aspects of design during mental categorization of design information in the generative phase, HYP 2 poses the relation between emotional aspects of design and its representations (See Figure 52).

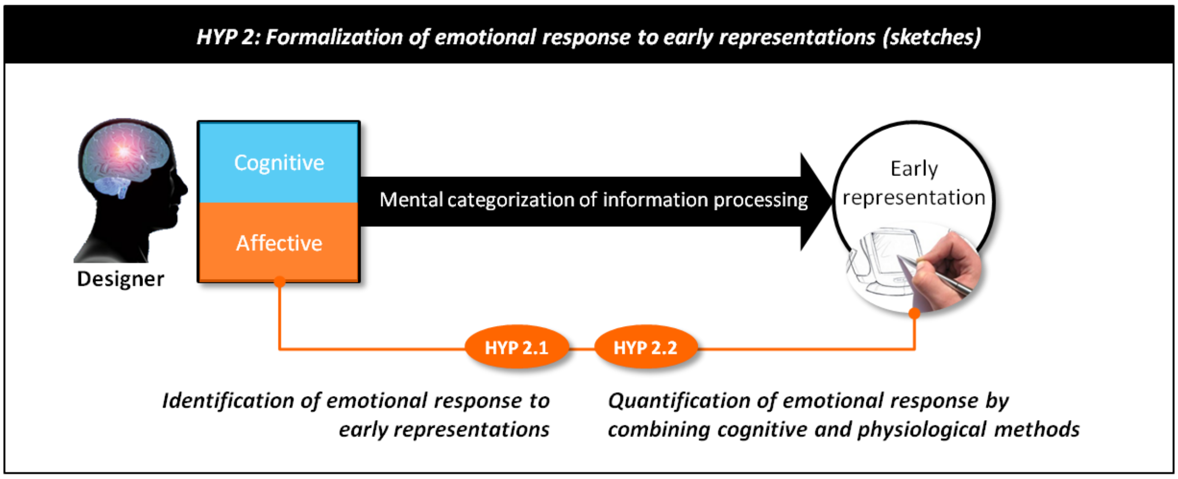


Figure 52. Structure of HYP 2

3.2.2.1 HYP 2.1 Identification of emotional response to early representations

In design research community, there is a growing interest in emotional design and pleasurable products. In order to increase emotional dimension of product, it is necessary to identify emotional response to early representations from the early stages of design. Given that designers start with their mental information, early sketches are the first externalization of this mental information in the generative phase. Thus, for our purpose, emotional response to early sketches is of great interest. As Figure 53 shows, we expect that early sketches may convey emotional values.

Figure 53. Designer intent and consumer response to product (Crilly et al. 2008)

Some pioneers have investigated semantic and emotional responses to product form at a certain level of abstraction as discussed in section 2.2.3.2, for example, shaded, rendered 2D, and 3D numerical prototypes. It cannot sufficiently reflect the relationships between early representations (sketches) and semantic/emotional words generated by designers in the early stages of design. Moreover, several studies, which have conducted an evaluation of early sketches, paid more attention to the creativity side of the product. Up to date, however, there has been no study, at the best of our knowledge, that investigate the emotions that early sketches elicited. Based on these arguments, the following hypothesis is put forth.

HYP 2.1: Emotional response to early representations (sketches) can be identified from the early stages of design. A link can be established between this response into sketches and into products. This way enables to anticipate the response of consumer.

3.2.2.2 HYP 2.2 Quantification of emotional response by combining cognitive and physiological methods

Following HYP 2.1 above, HYP 2.2 necessarily raised a question about which methods to choose to quantify the emotional responses to early representations. As shown in Figure 54, in many cases, cognitive methods have been extensively applied to quantify the semantic and emotional responses to product. In particular, the Self Assessment Manikin (SAM) by **Lang (1997)** is a pictorial questionnaire in terms of arousal, valence, and dominance. In addition, lexical emotional feelings, including a list of 50 emotional reactions proposed by **Geneva Emotion Research Group (1988)** in **Mantelet (2006)** enables to evaluate emotional responses in a questionnaire.

However, cognitive approaches are not able to assess in real time; and it is hard to catch objectively a subtle emotional state. Moreover, emotional response is hard to express in a lexical way. In order to account for the limitation of cognitive methods, recent studies in Kansei engineering start to triangulate these measures with physiological responses such as heart rate, electromyography (EMG), galvanic skin responses (GSR), and electroencephalography (EEG), etc. Undoubtedly, unnatural, obstructive and heavy instrument might interfere with respondent's natural way of design and may influence the results; however, applying physiological measurement under careful consideration could deepen our understanding of some respondent' unconscious emotional process **(Tran et al., 2003; Ganglbauer et al., 2009)**.

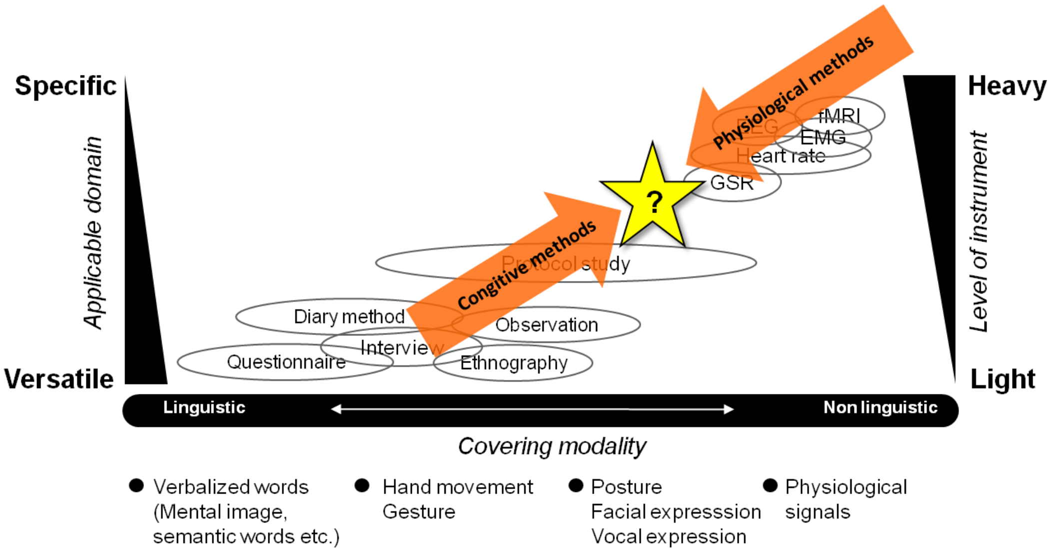


Figure 54. Toward a combination of cognitive and physiological methods

The correlation of results from cognitive methods and physiological methods will allow us to quantify the emotional response to early sketches. Moreover, we expect that the cognitive methods precise secondary emotion elicited by early sketches; physiological methods provide continuous and unconscious emotional state which is reliable to quantify. In summary, we proposed the following hypothesis:

HYP 2.2: Emotional response to early representations (sketches) can be quantified by combining cognitive and physiological methods

3.3 Conclusions

This thesis aims to explore how designers mentally categorize design information during early sketching performed in the generative phase. In order to achieve this, it is important to understand the relationship between cognitive and affective processes of designers and their representations together.

Thus, we raised a research question about ***"how can the cognitive and affective processes of designers be modeled, specifically, during the mental categorization of information processing performed in the generative phase?"***. To answer this research question, we developed two main hypotheses and their sub-hypotheses. HYP 1 brings together cognitive and emotional aspects of design and their mental processing; HYP 2 focuses on the relationship between emotional aspects of design and their early representations (early sketches) (See Figure 55).

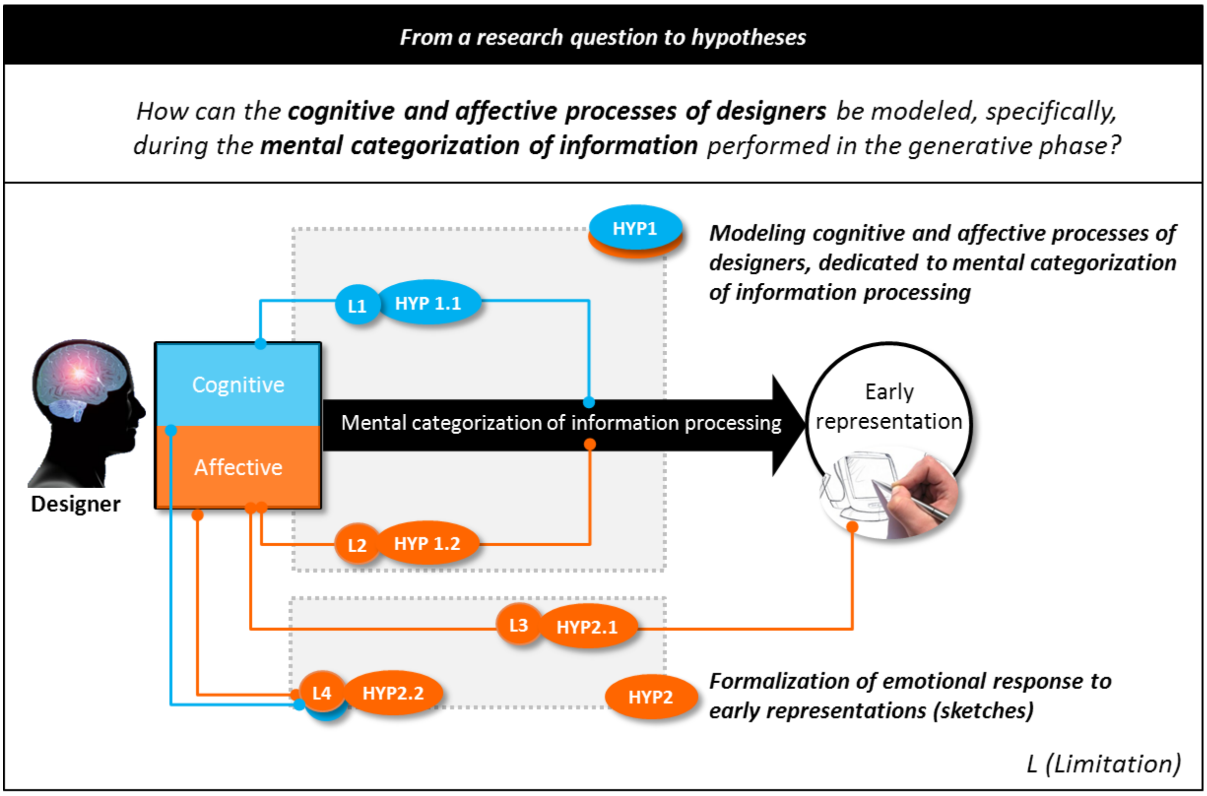


Figure 55. From a research question to hypotheses

IV. EMPIRICAL STUDY

Introduction

In chapter IV, two experiments were designed to test the hypotheses developed in section 3.2 (See Figure 56).

Experiment 1 (EXP 1) was consistent with HYP 1 and its sub-hypotheses (HYP 1.1 and HYP 1.2). EXP 1 aimed to formalize how designers mentally categorize design information during early sketching performed in the generative phase. We conducted a protocol study with sixteen product designers based on a descriptive memory model derived from cognitive psychology (See Figure 50). Our experimental field was the GENIUS project, which aims to develop the software tool for supporting designer's activities in the early phases of the design process.

Experiment 2 (EXP 2) was related to HYP 2 and its sub-hypotheses (HYP 2.1+HYP 2.2). The aim of EXP 2 was to identify emotional reaction to early representations (sketches). In order to quantify emotional response, it was necessary to combine and apply cognitive and physiological methods in current experiment.

Each sub-section includes results and discussion. Finally, this chapter concludes with validation of our hypotheses.

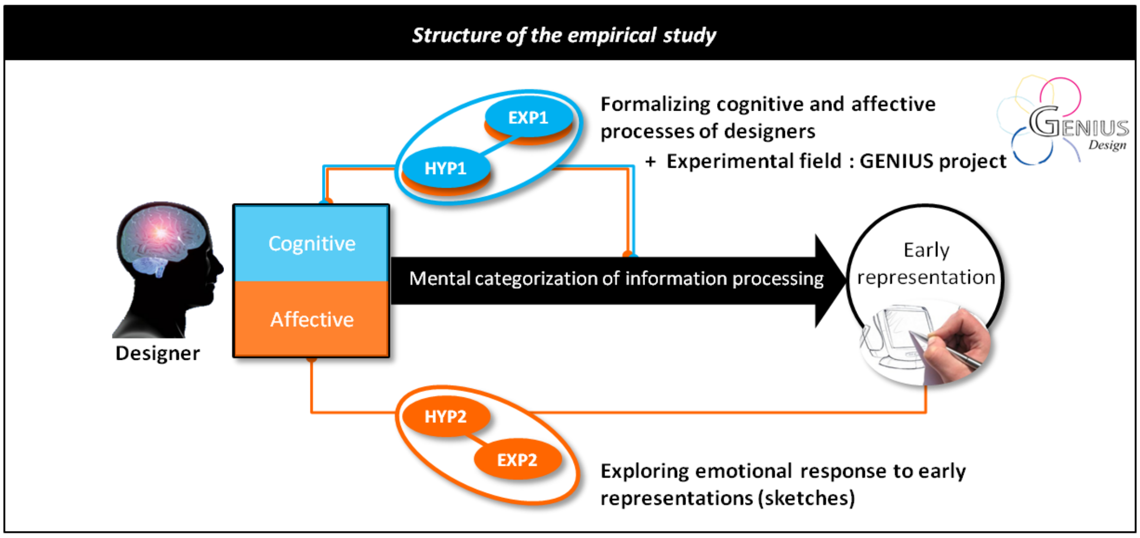


Figure 56. Structure of the empirical study

4.1 EXP 1: Formalizing cognitive and affective processes of designers

4.1.1 Experimental field: the GENIUS project

The GENIUS (*GEneration of New Image-based and User-centered Solutions for Design)* was a three-year project (2008-2011), supported by the Agence Nationale de la Recherche (ANR). The GENIUS has a primary objective to develop a system to support activities of product designers that would be dedicated to the early stages of the design process. The total budget of the project was 1.8M Euros, of which 900k Euros dedicated to our laboratory CPI.

4.1.1.1 Project objectives

The objective of project GENIUS was to develop a computational tool in order to stimulate the generative phases of design by the visualization of automatically generated shape. It included generation of solutions, sketches, identification of a "good form", etc. (See Figure 57). The work consisted of three progressive steps: (1) to formalize the designer's cognitive process for identifying the design knowledge, rules, and skills; (2) to translate design rules into design algorithms by employing Artificial Intelligence; and (3) to integrate virtual reality interface for supporting the both individual and collaborative working environment for designers.

The GENIUS project has applied a pull-push strategy, which concerned both user-centered and techno-centric design methodology. On the one hand (pull), the system provided the strong needs for business-oriented optimization of the product design process. On the other hand (push), technologies and new models of research in product design, and computer science had been proposed, tested, refined and validated in the real industrial workplace.

(a) (b) (c)

Figure 57. Examples of the GENIUS functionalities: (a) user scenario to support designer's individual work, (b) random generation of forms, (c) forms categorization (GENIUS D.7, 2009)

4.1.1.2 Project partners

The GENIUS project took advantage of interdisciplinary collaboration through the involvement of three universities and two industrial companies: Arts et Métiers ParisTech – LCPI (Project coordinator), Université Pierre et Marie Curie - LIP6, Paris 8- CHART (subcontracting), Immersion, and Diedre Design agency.

- ***Laboratoire Conception de Produits et Innovation, Arts et Métiers ParisTech (LCPI)***

Our laboratory CPI (LCPI) was a coordinator of the project. LCPI has worked for 20 years in the field of engineering design, specifically, toward optimizing the early design processes through developing new models and tools to be used. Their work included a deployment of design methodology, applied creativity, needs analysis, user evaluation, and so on.

- ***Laboratoire d'Informatique de Paris VI, Université Pierre et Marie Curie (LIP6)***

LIP6 is a research laboratory in computer science. The main area of expertise is the machine-learning technologies, including the development of artificial intelligence tools.

- ***Diedre Design Agency***

Diedre Design was founded in 1983 and has various design experiences, including automotive, sport product, packaging, etc. Their expert designers and interns have involved as for future end-user of the GENIUS system

- ***Immersion Corporation***

Founded in 1993, Immersion Corp. is a recognized leader in developing, licensing and marketing virtual reality solutions. The company investigates a benchmarking of existing design solution and develop cutting-edge interfaces integrating virtual reality and visual stimulation in this project.

- ***Laboratory Cognition & Usages (CHART), Paris 8***

CHART is an interdisciplinary laboratory, originated from the department of Cognitive psychology. They investigated a theory and methods used in cognitive psychology and gave recommendations to validate the experimental protocols and analysis.

4.1.1.3 Positioning of ''EXP 1'' within the GENIUS project

EXP 1 was related to the work package 2 of the GENIUS project: formalization of the cognitive design processes (Task 2.1). This task aimed to formalize the cognitive processes of designers in the generative phases wherein designers mentally categorize design information and generate new solutions. This process is partially observable through a series of sketches being developed by designers, and verbalized words by employing the method often used in cognitive psychology. Therefore, this experimental approach allowed us to both extract various types of information used by designers, as well as transformations they apply for such information. In particular, EXP 1 has been focused on the mental categorization of information processing during early sketching performed by designers.

During this experiment, our laboratory collaborated closely with the laboratory CHART to validate research theories and methods from a cognitive psychology viewpoint. Designers from the Diedre design agency have been actively involved as for future users (See Figure 58)

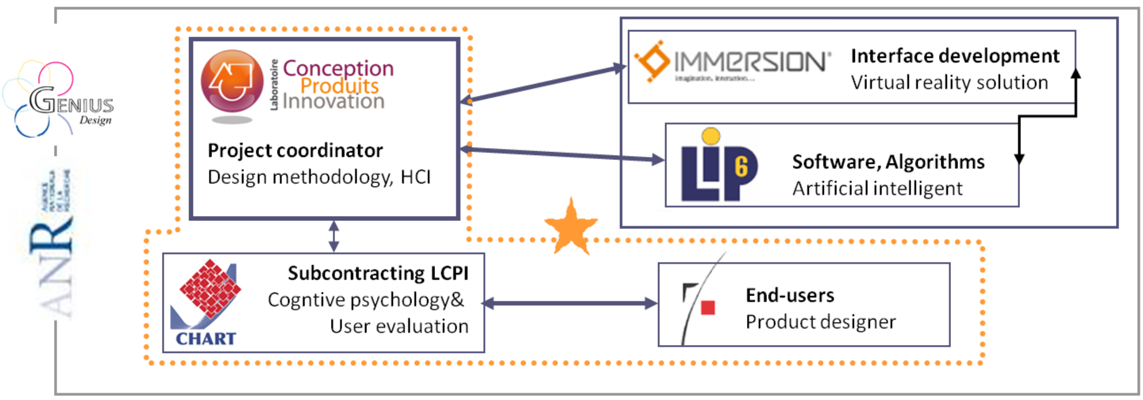


Figure 58. Positioning of EXP 1 within the GENIUS project

4.1.2 Objectives

The aim of EXP 1 was to formalize cognitive and affective processes of designers, which are dedicated to the mental categorization of information processing in the generative phase (See Figure 59).

The objectives were:

- to quantify what kind of mental information is extracted and how it can be transformed or categorized through cognitive operations during early sketching;
- to explore affective processes of designers which would interplay with their cognitive processes in generating stimuli and evaluating their results during the generative phase;
- to identify similarities and differences in design activity between novice and expert designers.

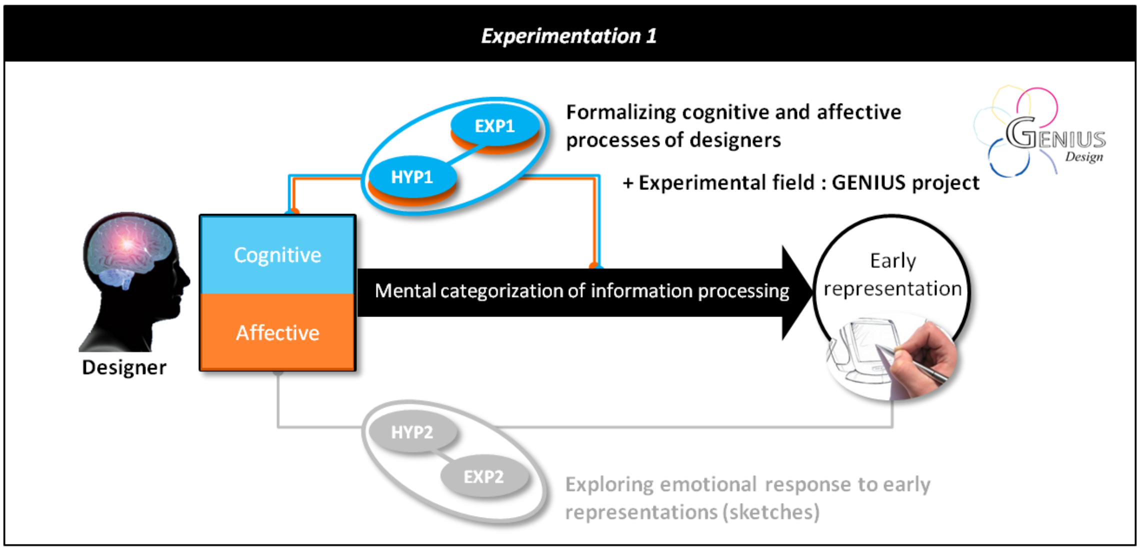


Figure 59. Structure of EXP 1

4.1.3 Method

As noted in the state of the art (§2.3), a comprehensive and varied research method is required for understanding information and activities related to design **(Cross et al., 1996)**. In many cases, some methods have been based on the explicit representations used or produced by designers; therefore, they have certain limitations since many cognitive activities of designers during the early stages of the design are implicit. One approach to this issue is provided by methods drawn from ethnography **(e.g. Blomberg et al., 1993; Buciarelli, 1994; Lawson, 1990; Cross et al., 1996; Lindlof & Taylor, 2002)**. Data collected using an ethnographic methodology often derives from observations, interviews, and questionnaires completed in real contexts rather than from the results of laboratory experiments. Another approach concerns the think-aloud method, which is based on observations and verbalizations occurring in real time under experimental environment **(e.g. Akin, 1976; Cross et al., 1996; Suwa & Tversky, 1997; Eastman, 2001; Bilda & Gero, 2007; Coley et al., 2007)**.

The verbalization and its subsequently protocol analysis became the most popular experimental technique used in design research for capturing, understanding, and analyzing of design thinking **(Gero & Tang, 2001; Cross, 1997, 2008; Bilda, 2006; Coley et al. 2007)**. Generally two types of think-aloud methods have been used: concurrent and retrospective. The concurrent protocol may point out detail sequences of information process reflecting the designer's working memory (WM); therefore, it has been utilized to reveal the process-oriented aspects of designing **(Ericsson & Simon, 1993; Dorst & Dijkhuis, 1995)**. The retrospective protocol has been used in experiments which focus on content-oriented aspects because it may retrieve the trace of the cognitive process and reveal information partially in both working memory (WM) and long-term memory (LTM) **(Dorst & Dijkhuis, 1995; Gero & Tang, 2001)**.

Especially, the concurrent verbalization method was appropriate for EXP 1 in that we focus on the kind of mental information and cognitive operations related to the different types of memory: sensory, working and long-term. However, as **Coley et al. (2007)** reported, the think-aloud method may result in interferences in designer's nature activity. For example, some thoughts cannot be verbalized and might cause a distortion in thinking. In order to compensate the deficiencies of the concurrent methodology, we conducted semi-directive interviews at the end of experiment. Following the guide from **Lindlof & Taylor (2002)**, the interviewer provides various questions to suit respondent. In utilizing the sketches generated by designers as a cues, the interviewer repeats broad and open ended questions until we can gather the information which our research aims at, for example, 'what did you think when you received the design brief?', 'tell me more about your thinking on that', or 'what is that?' etc.

However, given that there are still possible problems of employing the concurrent verbalization method, we conducted three pilot studies in order to verify our protocol and test design brief (→§ 4.1.3.3).

4.1.3.1 Participants

As a part of three pilot studies, a total of six master students of Arts et Métiers ParisTech took part in the experiment. They had minimum three years of academic industrial design training.

During the main experiment, we recruited eight expert designers and eight novice designers (10 men and 6 women, all French-speaking participants). The eight expert designers had an average of 10.3 years of experience. If two experts who had worked in the product design field for over 20 years were excluded, the mean number of years of professional experience decreases to 5.7 years. The novices were varied from undergraduate, master, to PhD students in industrial design. They all have experienced design internship in design agencies and involved limited product design projects or research. Nine participants had been working in the same design agency.

4.1.3.2 Equipment

The experiment was conducted in working place of participants in order not to change natural environment and minimize external stimuli. As shown in Figure 60, we used two video cameras and one voice recorder to collect verbalizations. One video camera captured the movements of the hands of each designer and recorded close-ups of the sketches, and the second recorded the entire body of the designer.

Figure 60. Equipment positions

4.1.3.3 Procedure

The protocol involved three stages: warm-up exercises, concurrent verbalizations and semi-directive interviews.

1) **Warm-up exercises,** in which we explained the procedure of the experiment and participants became accustomed to the practice of concurrent verbalization (~15 min);

2) **Concurrent verbalizations,** in which participants were asked to work on the design brief: Designing a Nike vacuum cleaner. During this phase, they started to generate early sketches using traditional sketching tools and simultaneously verbalized their thoughts (~60 min);

3) **Semi-directive interviews** about the mental images, semantic descriptors, and forms generated as well as about the relationships among those three types of information (~15 min)

During the experiments, participants were encouraged to use all of their given time for carrying out the task. The interventions of the experimenter were as small as possible to remain neutral.

Next, we collected the entire verbal protocols and their comportment of designers during the task. They were transcribed and coded according to our coding scheme (see Table 9). The video analysis software INTERACT was used to this analysis processing. Section 4.1.3.5 presents the detailed protocol analysis process.

4.1.3.4 Pilot studies and protocol validation

We carried out three pilot studies in order to validate our protocol design. Six novices have been involved in the pilot studies. Table 8 shows a summary of the considerations for the pilot studies and their control conditions.

Table 8. Summary of pilot studies

	Pilot study 1	Pilot study 2	Pilot study 3
Participant	2 novices	2 novices	2 novices
Objective	Validation of design brief	Comparison between the retrospective and concurrent protocols	Validation of the concurrent verbalization method with physiological measurements
Condition	Condition 1: designing a vacuum cleaner for young couple between 20s-30s Condition 2: designing a Nike vacuum cleaner	Condition 1: retrospective protocol Condition 2: concurrent verbalization protocol	Condition 1: concurrent verbalization protocol alone Condition 2: concurrent verbalization with galvanic skin response (GSR)
Method	Concurrent verbalization protocol	Verbalization protocol (retrospective/concurrent)	Combination of cognitive and physiological method

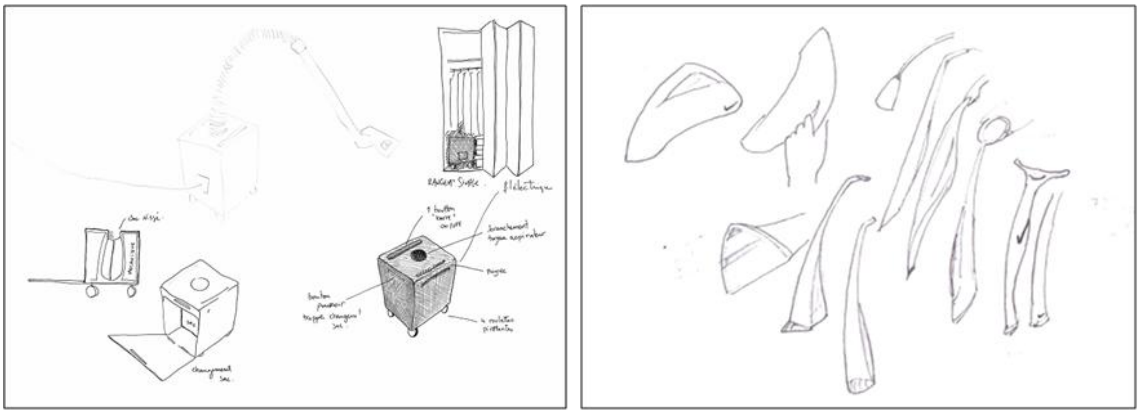
- ***Pilot study 1 : Validation of design brief***

Condition 1: Designing a vacuum cleaner for young couple between 20s-30s
Condition 2: Designing a Nike vacuum cleaner

Pilot study 1 was designed to validate different types of design brief. Two novices took part in this pilot study. Design brief can be varied at different levels of constraints, including its abstraction, product characteristics, and project length. In our case, design brief should not to be too function-oriented because we needed to collect various levels of design information from low-level to high-level information, such as values, semantic words, etc. In addition, design brief had to be at reasonable levels of complexity to generate the first idea under sketching condition within one hour. Moreover, it had to be attractive to motivate designers to participate actively in a protocol study.

Therefore, we first selected product categories 'a vacuum cleaner', which was one of the familiar home electronics and had a reasonable complexity in terms of functions and components, including handle, filtering bag, hose, suction, etc. Design brief of vacuum cleaner was then varied in two conditions: with the brand name 'Nike' or without one. As we defined in a protocol described in section 4.1.3.3, two designers were asked to think aloud simultaneously during sketching under the condition of two design briefs. After the completion of verbalization session, the participants were asked to report how they felt about a design brief.

Under these experimental conditions, we observed that the information process regarding a link among mental images, semantic words, and forms do not have significant differences. However, the quantity and a variety of design information verbalized demonstrated interesting differences. We found that designers interpreted more easily a design brief in associating the ''Nike' brand (condition 2). For example, one designer under condition 1 formulated design problem related to user context, including small studio, limited budget, frequent usage, etc. Comparatively, the other designer under condition 2 oriented design problem to convey new values of the ''Nike'' brand within a vacuum cleaner. Moreover, there were much greater variability of design outcomes with the ''Nike'' brand (condition 2) than without the brand name (condition 1) as shown in Figure 61.



(a) *(b)*

Figure 61. Examples of sketches under two conditions: (a) without the brand name; (b) with the brand name 'Nike'

Therefore, this combination between two distinct sectors, such as a sport brand "Nike" and an electronic application "a vacuum cleaner", enables designers to produce various combinations of design information. Therefore, we decided to select the design brief 2: 'designing a Nike vacuum cleaner' for the main EXP 1.

- ***Pilot study 2 : Comparison between retrospective and concurrent protocols***

Condition 1:	Concurrent verbalization protocol
	Design brief: designing a NIKE Vacuum cleaner
Condition 2:	Retrospective verbalization protocol
	Design brief: designing a bag for young sportive girl

Pilot study 2 was designed to validate the concurrent verbalization protocol. Two novices were involved in this pilot study. As explained in section 2.3.2.1, the concurrent verbalization protocol might influence the nature of the design process and cause discomfort during sketching. In order to raise this issue, we varied two conditions of verbalization: concurrent or retrospective protocol as described by **Ericsson and Simon (1980; 1984)**.

In order to have both the concurrent and retrospective protocols from a single design session, we used four phases: warm-up phase, concurrent protocol, retrospective protocol, and semi-directive interviews. We prepared a short break between the concurrent and retrospective protocol stages. During the concurrent protocol, designers were asked to verbalize about what is passing through their mind, rather than describing what they do and why. During the retrospective protocol, they were not required to verbalize concurrently during designing; instead, designers were questioned about their design processes and types of mental information generated at the end of the experiment. In order to assist the recall of their activities, we used their sketches as cues during a retrospective protocol. As a result, the analysis of two conditions did not demonstrate any differences in the quantity of sketches. Even though some participants had doubted about whether this method was feasible or not, after the test the responses were positive. For example, one of participants commented that concurrent verbalization enable her to generate ideas being much clear and reasonable. Meanwhile, due to the inter-individual differences, we observed that some designers were apt to express verbally their thought; the others were not.

Consequently, pilot study 2 has partly confirmed that concurrent verbalization method did not influence natural activities of designers in the generative phase. However, there are still uncertainties, including levels of expertise, personality, etc. Therefore, we decided to employ semi-directive interviews to gather complete metal information.

- ***Pilot study 3 : Validation of concurrent verbalization method with physiological measurements***

Condition 1:	Non-verbalization + GSR *Design brief: designing a perfume bottle for young professionals*
Condition 2:	Concurrent verbalization + GSR *Design brief: designing a NIKE vacuum cleaner*

During pilot study 2, we tried to examine possible differences between the concurrent and retrospective verbalization protocols. Apparently, designers interviewed positively about concurrent protocols; however, we still had a question about how concurrent method causes discomfort of designers at an unconscious level. At the same time, we would like to explore how physiological measurements can detect affective responses of designers during cognitive processes.

Therefore, as discussed in section 2.3.4, we decided to combine cognitive and physiological measurements during this pilot study 3. Our criteria for determining the biosensors involved non-obstructiveness during sketching and verbalization condition. The biosensors must provide continuous information, be easy to interpret signals, and have a high reliability. Hence, we intended to apply galvanic skin response (GSR), which could indicate effective correlation to arousal and satisfy criteria mentioned previously.

In order to have both conditions from a single design session, we used four stages: warm-up exercises, retrospective protocol (condition 1), concurrent protocol (condition 2), and semi-directive interviews. Between two conditions, a short break was given. As shown in Figure 62, the two GSR electrodes were placed on two fingers of the left hand. Changes in the skin conductance were collected at 200Hz per second. Using the BIOPAC acquisition unit and the software BSLPro 3.7, we could amplify the collected signal and visualize it.

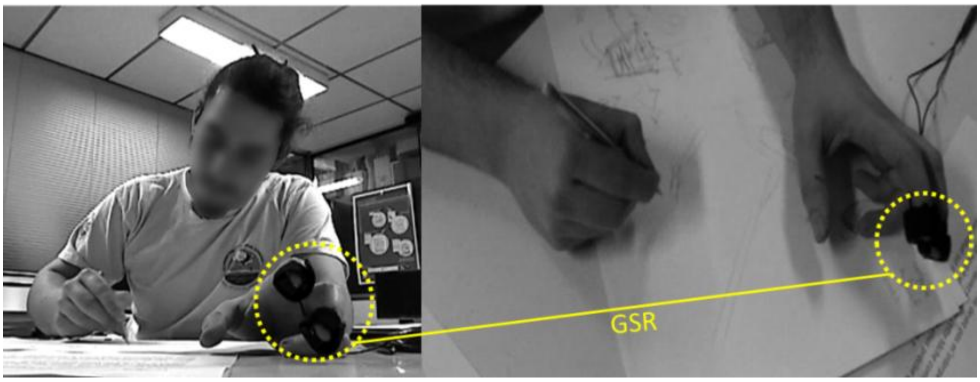


Figure 62. Design of protocol in condition 2

Before the analysis process, the collected data was reduced and filtered using the software BSLPro 3.7. GSR captured was then more manageable without noisy signals, but still preserved the main features of the GSR distribution. Two analyses were conducted. The first was a number of peak occurred within the GSR graph. The second was troughs of GSR values in time. The results are illustrated in Figure 63.

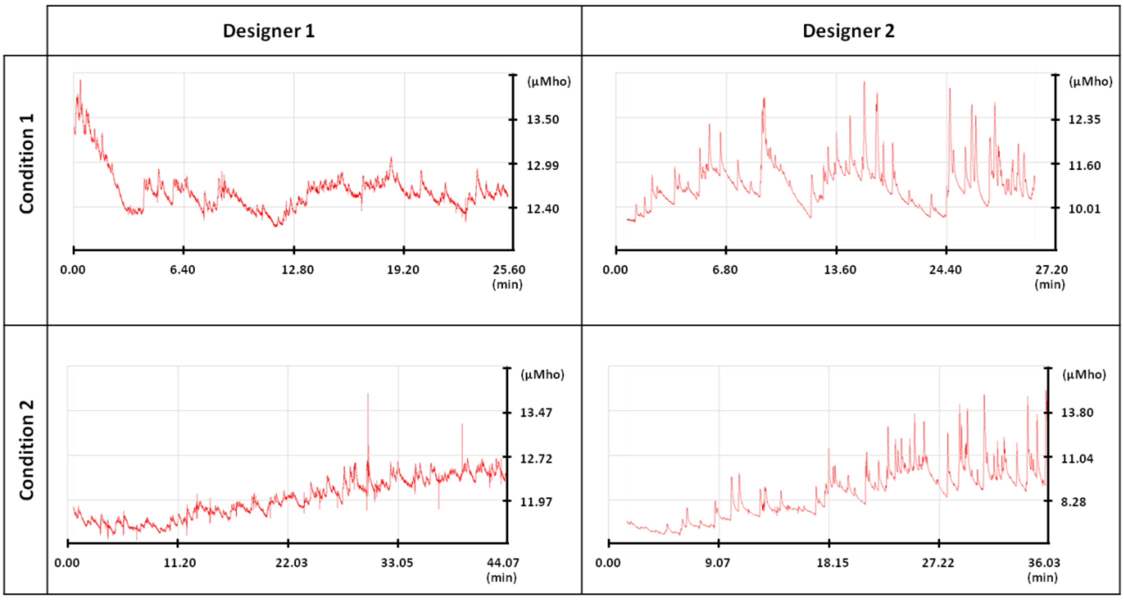


Figure 63. Change in GSR values for two conditions

As a result, we did not find any significant difference between non-verbalization and verbalization conditions. Both conditions showed unexpected peaks and irregular tendency of GSR values. It seems that (1) verbalization condition might influence on GSR values; (2) two fingers of the left hand might be pressed so that a wrong GSR signal sent while designers move a sketch against the sheet beneath; or (3) employing GSR electrodes more than 30 minutes might heat up the measurements and cause unusual rising GSR value. However, Galvanic Skin Reponses (GSR) is still interesting measurement owing to their advantages, including cheap, easy to apply, high sensibility, reliability, etc.

4.1.3.5 Protocol Analysis: coding scheme

- ***Coding method***

Most of the previous protocol analysis methods have been used to divide the entire verbal protocols into small units, namely segmentation (also called segment) and code using own suitable coding scheme (**Goldschmidt, 1991; Suwa et al., 1998**). Using the principles of protocol analysis recommended by **Suwa & Tversky (1997) and Gero & McNeill (1998)**, the verbal protocols were transcribed and segmented for coding according to our coding scheme (See Table 9). Next, written transcripts were attached to corresponding video clips. The video analysis software INTERACT was used to reduce the time involved in this process and to produce reliable quantitative results (See Figure 64).

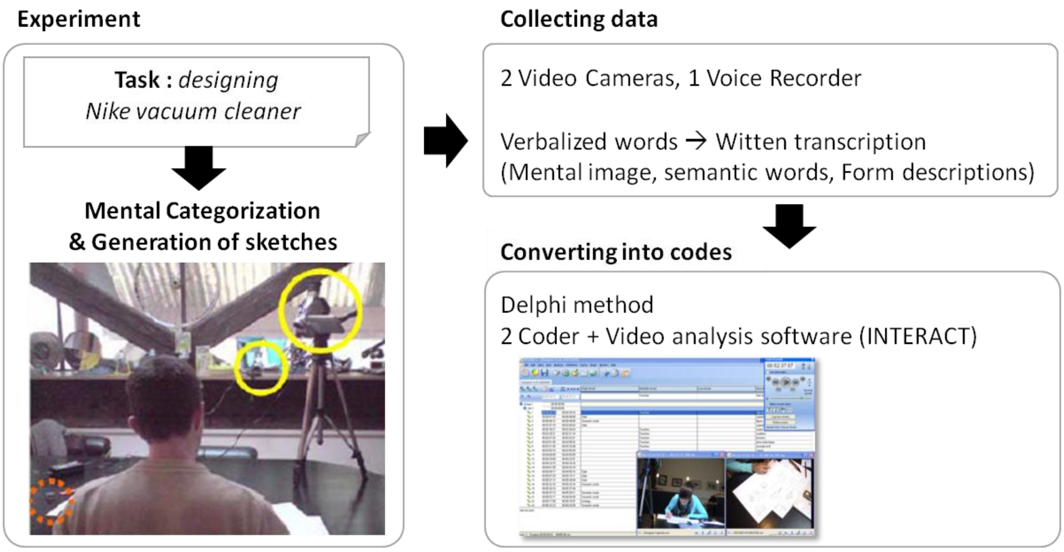


Figure 64. Protocol analysis

- ***Coding scheme for design information, cognitive operations, and vocal expressions***

Our coding scheme consisted of three categories: design information, cognitive operations, and vocal expressions (See Table 9). The first two categories referred to verbalizations; one category concerned verbal expression. **First, the coding scheme for design information** was primarily based on our previous work of *Kansei* words **(Bouchard et al., 2008, 2009; TRENDS D2.3, 2009)**. The Kansei words include semantic descriptors, objects names, and low-level descriptors. The level of information can be understood in terms of position on an axis from abstract (*high-level information*) to concrete (*low-level information*). They consist of 3 levels of design information (high, middle, low), and 10 categories *analogy (Ha), semantic words (Hs), values (Hv), style (Hy), sector name (Ms), context (Mc), function (Mf) , color (Lc), form (Lf), texture (Lt)*.

Second, the coding scheme for cognitive operations was based on our descriptive model presented in section 3.2.1.1. Table 9 lists six categories of cognitive operations, involving selective attention, visuospatial attention, questioning, association, transformation, and judgment/decision. Full details are given in Appendix A. They were primarily based on the Geneplore Model **(Finke et al., 1992)** and partly selected from the coding scheme of **Suwa & Tversky (1997).** Specifically, among cognitive operations, association and transformation are of particular interest because they are related to the process whereby information is retrieved from long-term memory and stored in short-term memory. The complete coding scheme enables to understand the connections between mental representation during retrieval and external information during sketching, and yields an encompassing depiction of the cognitive processes involved in categorizing design information. It should be noted that we coded ''*Silence''*, which is not a cognitive operation, when designers did not verbalize their thoughts and remained silent. We did so because we expect that this code facilitates the anticipation of certain internal cognitive processes, which are rarely verbalized but that may enrich our model. In addition, responses consisting of replicas of a given design brief, expressions of needs/difficulties, jokes, and so on were coded as "other". This code was set aside for further study (the percentage of the "other" response was negligible compared with those of other responses in this experiment).

Third, the coding scheme for vocal expressions was developed from the work of **Ludden (2008), Reisenzein et al. (2000), and Russell (2003).** They include four categories, consisting of verbal acknowledgement, surprise vocalization, laughter, and uncertainty. Spontaneous vocal expressions referred to both cognitive and emotional response. For example, 'aha', or 'ok' was coded as verbal acknowledgement, which may reflect cognitive responses to the solution. In case of 'surprise vocalization', it referred to 'a feeling of surprising', through uttering sounds of words, such as 'oh', 'wow', or 'super', etc. This is way, each vocal expression can be related to a specific emotional state. Moreover, employing coding scheme for vocal expressions may provide objective results.

Table 9. Protocol coding scheme: "Design information", "Cognitive operations", and "Vocal expressions"

Coding(Code)		Description	*Examples*
Design information (Bouchard et al., 2008, 2009; TRENDS D2.3, 2009)			
High level (H)	**Values (Hv)**	These words represent final or behavioral values	*Security, Well-being*
	Semantic words (Hs)	Adjectives related to color, form, or texture, but also impressive words in the field of Kansei Engineering	*Playful, Romantic, Aggressive*
	Analogy (Ha)	Objects in other sectors with features to integrate in the reference sector	*Rabbit →Speed*
	Style (Hy)	Characterization of all levels together through a specific style	*Edge Design, Classic*
Middle level (M)	**Sector name (Ms)**	Object names describing one sector or sub sector being representative for expressing a particular trend	*Sports*
	Context (Mc)	User social context	*Leisure with Family*
	Function (Mf)	Function, usage, component, operation	*Modularity*
Low level (L)	**Color (Lc)**	Chromatic properties using qualitative or quantitative	*Yellow, Light blue*
	Form (Lf)	Overall shape or component shape, size	*Square, Wavy*
	Texture (Lt)	Patterns (abstract or figurative) and texture	*Plastic, metallic*
Cognitive operations (Finke et al., 1992; Harris, 1992, Suwa & Tversky, 1997; Ball & O'Callaghan, 2001; Style, 2005)			
Selective attention		Selectively concentrating on one aspect of outer/inner senses	*(In watching the bicycle wheel) 'I had seen the mini- sports shoes on the bicycle wheel in the show window'.*
Visuospatial attention		Interpretation of visual information, such as depict elements on sketches for arranging the spatial relations on sketches	*In profile, the screen should be this side for little more user-oriented, then a gripe on the right side.*
Questioning		An expression of inquiry about ideas and emerging issues not associating with one another	*Does it feel sportive? It is a little static; I think that we want to something trendy.*
Association		Grouping ideas, finding similarity/uniformity, and difference/contrast	*If I start by an iPod which has a hard angles to differentiate into two components, fine plastic and bright/clean color, …*
Transformation		Ideas are shifted to make interesting and useful entities such as new value and analogy	*There is an automated vacuum cleaner, like a robot, which can move by itself.*
Judgment/Decision		Make a judgment or evaluation on ideas according to the design brief, related to design information, or satisfaction of designer	*I like/dislike this form.*
Vocal expressions (Reisenzein et al., 2000; Russell, 2003; Ludden, 2008)			
Verbal ac-knowledgement		Reflecting cognitive responses to the solution words	*'aha', 'oh yes' , 'see', 'ok', 'that's it'*
Surprise vocalization		Uttering sounds or words when sth/sb gives a feeling of surprise	*'oh', 'wow', 'super'*
Laughter		Feeling fun and amusements	*'haha', 'that's interesting', 'funny'*
Uncertainty		Being unsure about what he or she felt	*'well, hmm', 'I don't know'*

4.1.4 Results

In this section, based on the video and audio protocols, we intended to identify what kind of mental information is extracted from memory and to determine how this design information is transformed or categorized during early sketching. We subsequently applied our coding scheme including design information, cognitive operations, and vocal expressions (See Table 9). The qualitative and quantitative analysis of the results is summarized in the following subsections:

- Idea categorization map → § 4.1.4.1
- General statistics → § 4.1.4.2
- Structure of design information →§section 4.1.4.3
- Cognitive operations during the mental categorization of information processing → § 4.1.4.4
- Exploratory vocal and facial expressions →§ 4.12.4.5
- Comparison between novice and expert designers →§ 4.1.4.6

4.1.4.1 Idea categorization map

In order to examine what kind of mental information are extracted and how these can be transformed or categorized during early sketching, an *Idea categorization map* was developed in this study. It is composed of verbalized keywords and external representations (e.g. early sketches). While many previous protocol analysis methods have worked with the agreed notion of 'segmentation' **(Goldschmidt, 1991; Suwa et al., 1998)**, our way of visualizing is based on the notion of 'idea', which is comparatively a much bigger chunk than a 'segmentation'. Idea was composed of several segmentations and keywords.

As Figure 65 illustrated, axis X represents the timeline of each idea in which we can observe the transformation of designer's mental information into the single idea, Axis Y represents the global timeline during the task in which the information is categorised by retrieving and transforming the previous ideas.

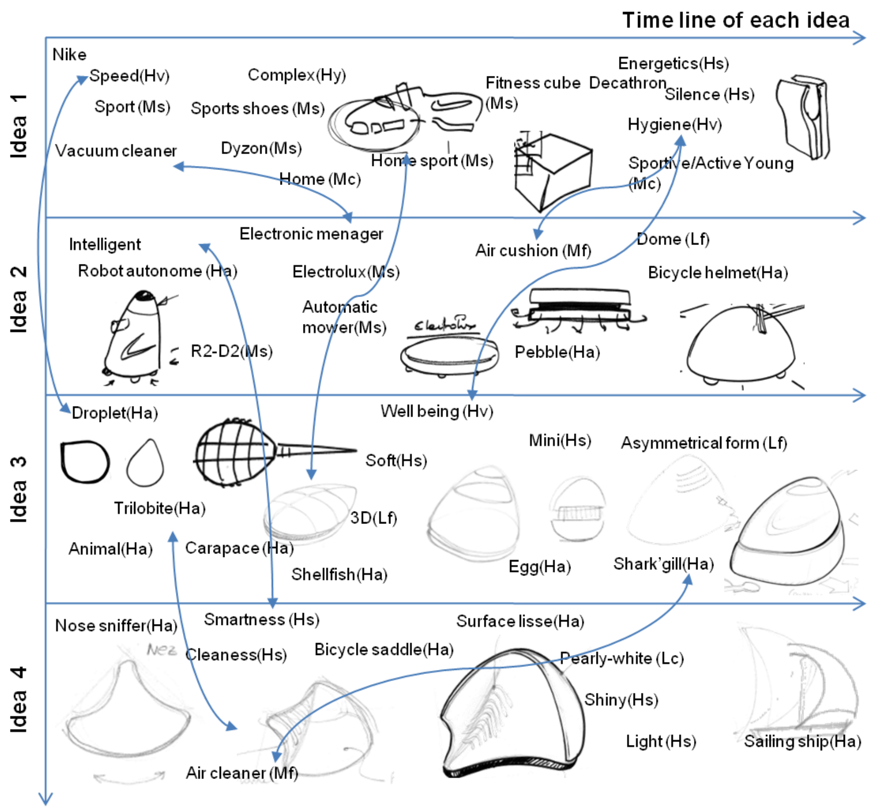


Figure 65. Idea categorization map based on Designer 5's work (Expert) (Kim et al., 2009b)

Once expert designer (D5) had read the given design brief 'Designing Nike vacuum cleaner', **in idea 1**, he started retrieving design information from his memory and verbalizing it "I need to try to understand what a vacuum cleaner is", "Nike is a sport'', etc. The combination of the related sector name became an idea of 'home sport'. At this moment, some adjectives appeared in designer's mind such as energetic, speed, etc., and some verbs and nouns to describe his mental representations. Designer also set the expected context such as 'for sportive and active young' and values of 'hygiene'.

In idea 2, a vacuum cleaner was a sort of electronic manager (revisited idea1). Among the electronic managers, designer retrieved a ''pebble'' and an ''automatic mower'' through a chain of mental images and transformed them into a ''total automatic intelligent robot'' in adding the product value 'intelligence'. Then ''dome'' shape, like ''bicycle helmet'' was associated due to the similarity to the form. **In idea 3**, he was interested in the form of droplet to represent how fast/speedy (Hv) Nike sports shoes are (revisited Idea1). It becomes transformed into other sectors including animal, trilobite, shellfish, etc. in relation to their formal attribute. Then, he associated the previous values of ''hygiene'' (revisited Idea1) with current value of ''well-being''. **In Idea 4**, the designer rearranged and reassembled previous elements ''trilobite'' and ''animal'' (revisited Idea3) to make interesting idea in joining the semantic words ''smartness' and ''cleanness''. They were described with low-level attributes: color and texture such as smooth surface, shiny, pearly-white, etc. The idea about "the air filter grille looks like a shark fin" was replicated in Idea 4. The arrows indicate how to follow the designer's idea flow.

Here is another example from novice designer (Designer 7) in Figure 66.

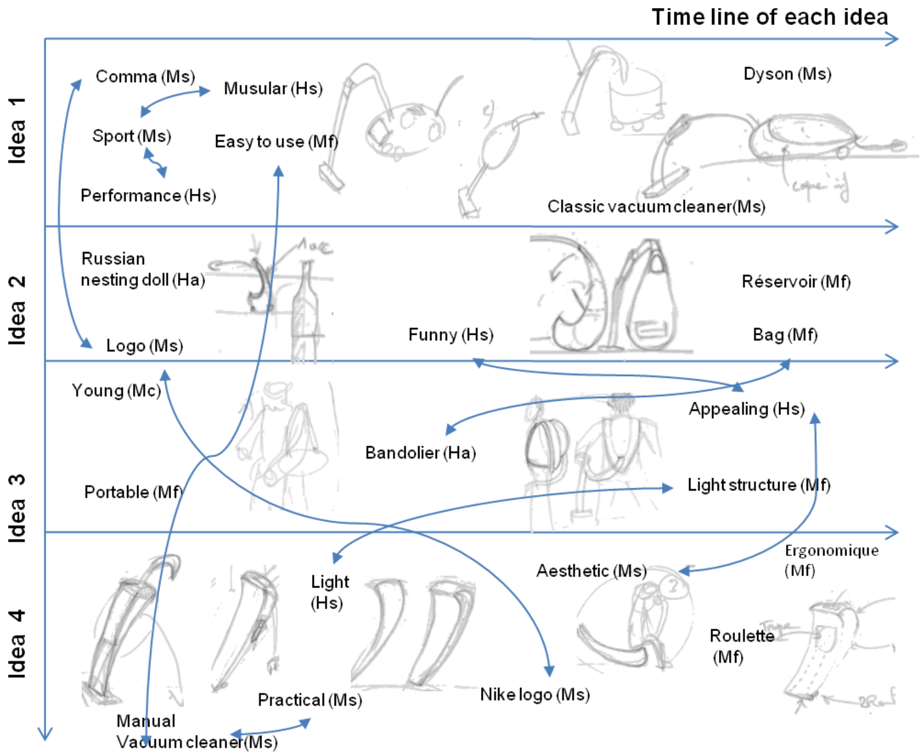


Figure 66. Idea categorization map based on Designer 7's work (Novice)

In idea 1, having read the given design brief, Designer 7 first thought about the Nike logo and then began with the strong performance of NIKE, involving very masculine, practical, etc. On the other side, designer illustrated existing types of vacuum cleaner. He considered ‘‘Dyson’’ as a representative vacuum cleaner, which can be characterized as a ‘‘easy to use’’ and ‘‘masculine’’ vacuum cleaner as he verbalized before. **In idea 2,** during he enjoyed with a form of NIKE in a vertical view, ‘‘Russian dolls’’ just came up designer’s mind. He was then looking for something fun and appealing vacuum cleaner. **In idea 3,** designer thought a ‘bag’ type of vacuum cleaner can be general. He imagined the context of the use for the young. **In idea 4,** he developed the concept with ‘a form of Nike LOGO" and "manual Vacuum cleaner". At the same time, he was looking for another form of NIKE vacuum cleaner, which is more light, practical, and aesthetic.

In summary, the findings from this qualitative analysis carry three implications. First, a series of cognitive operations engaged by the designer was identified. It may come from iterations between the sketches and mental information by applying analogies or reference sectors. They may enable to transform an idea, and/or move from one idea to another. Second, when generating sketches, designer can strengthen their ideas with semantic words rather than existing products. Third, we observed the continuity and discontinuity of idea flow. It may imply that there is a certain cognitive catalyst to link designer’s mental process. A comparison between previous ideas and current ideas help designers to make a decision or evaluation on the outcomes. Further discussions will be described in section 4.1.5.1.

4.1.4.2 General statistics

- **Reliability of the coding process**

As we explained in section 4.1.3.5, we divided the entire verbal protocols into small units, that is, segmentation **(Goldschmidt, 1991; Suwa & Tversky, 1997)**. The way of segmentation was when there is a change in the designer's intention, the contents of their thoughts, or their actions. Therefore, one segment does not mean one sentence; sometime it could contain many sentences. In our present protocol, the average number of segment was 112.5; and the average length of the time for a segment was 31 seconds.

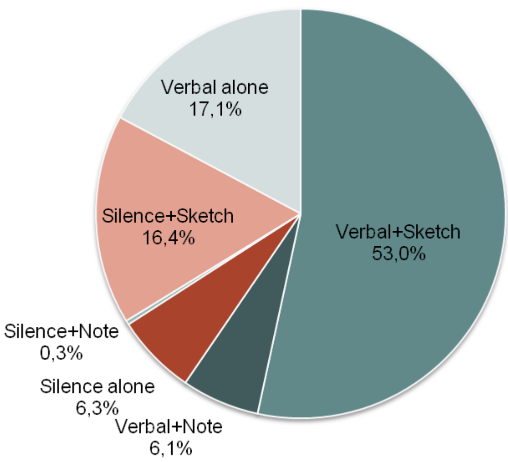
To increase a reliability of the coding process, we used the Delphi method involving two coders as described by **Gero & McNeill (1998)**. Each protocol was coded by two coders separately. Thus, coding process consisted of three stages: the first run by one coder, second run by another coder, and lastly an arbitration phase where codes were selected and accepted by two coders together. The reliability of the coding process was calculated using the percentages of inter-coder agreement (see Table 10). This figure was higher than 86%, which indicated that the coding process was reliable. Videotaped sketches were also used to complete and verify verbalized contents.

Table 10. Coding consistency with agreement percentages between different coding stages

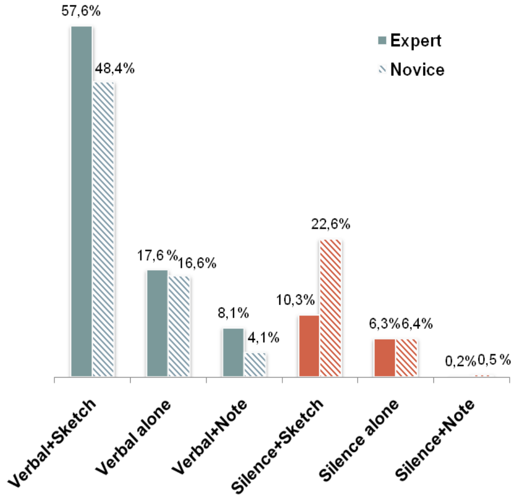
Agreement percentages between		
1st and 2nd coding (%)	1st and arbitrated coding (%)	2nd and arbitrated coding (%)
86.0	90.4	93.0

- **Modality of gathering information engaged by designers**

In our specific study, Figure 67a illustrated that designers verbalized their thoughts during 76.2% of the session and remained silent for 23.8%. During more than half of the time (53.0%), designers simultaneously verbalized and generated sketches. They generated sketches without verbalizing for 16.5% of the protocol only. In addition, we compared this modality of gathering information between novices and experts as shown in Figure 67b. According to the results from two-way ANOVA (with replication) test, there is a significant difference in between the novice and expert designers wherein they verbalized their thought simultaneously during sketching and taking a note (F critical = 0.02, P=0.48). Expert designers more easily verbalized their thought simultaneously during sketching or taking a note than novice designers did.



(a)



(b)

Figure 67. Occurrence percentages of design activity

4.1.4.3 Structure of design information

The verbalized keywords were counted with basis on the our coding scheme (Table 9) which consists of the 3 levels (*High, Middle, Low)* and 10 categories *analogy (Ha), semantic words (Hs), values (Hv), style (Hy), sector name (Ms), context (Mc), function(Mf) , color (Lc), form (Lf), texture (Lt)*). Figure 68 shows the frequencies for each level of design information. On average, middle-level information was used most frequently (41.8% ±10.1) followed by high-level (40.1%± 9.9) and low-level (18.1%±6.9) information. Thus, high- and middle-level information accounted for 81.9% of the words verbalized during early sketching. Low-level information tended to be represented in sketches rather than verbalized words.

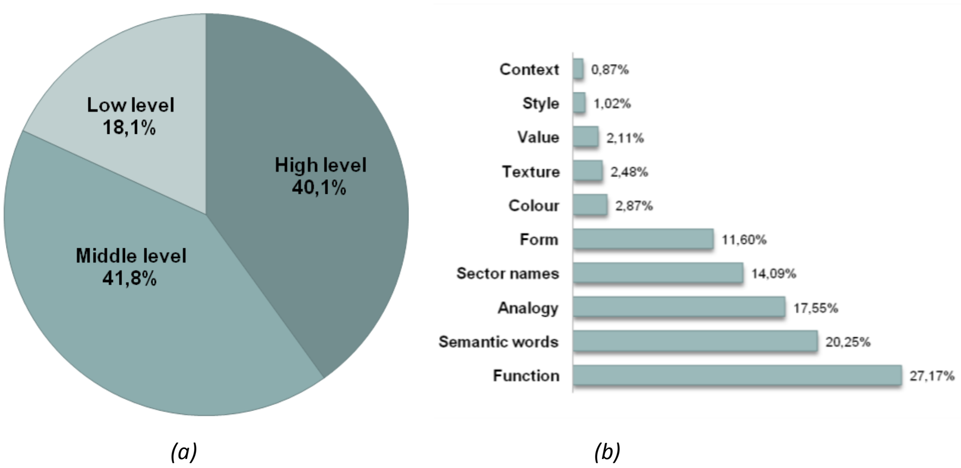


Figure 68. Frequencies of each level of design information

The detailed frequencies of each category are presented in Figure 68b. The most frequently verbalized word was related to *function* (27.2% ±8.6), integrated part of the internal mechanics, units, usage and operation principal, for example, 'fan', 'dust bag', 'air-cushion', and so on. This was followed by *semantic words* (20.3% ± 8.7), including often semantic adjectives related to color and form, for example sportive, dynamic, organic, etc. The third category concerns *analogy* (17.6% ±8.3), other fields such as nature, fashion, sports, and architecture. The forth category includes *sector name* (14.1% ±7.0), *form* description (11.6% ±5.5) in low-level information related to shapes and silhouettes. They were usually brought together directly when designer are sketching. The remaining five categories were mentioned relatively less frequently: *color* (2.9% ±2.6), *texture* (2.5% ±2.0), *values* (2.1% ±2.4), *style* (1.0% ±3.4), and *context* (0.9% ±1.2).

- **Sector of analogy**

The substance of the comments made by the designers was very dependent on a given design brief: ''Designing a Nike vacuum cleaner''. For example, representative words in values categories included ''dynamism'' and 'aesthetics'', and the most common semantic words included ''sportive'', ''dynamic'', ''fluid'', ''classic'', ''technical'', ''fun'', ''friendly'', and so on. Designers also employed twelve analogical words referring to, for example, sports (using a harness or scooter, lifting weights, using flippers, cycling, dancing, etc.), biomorphism (animals: shark fin, humans: mouth, and vegetables), shoes & luggage (backpacks, accessories, etc.) (See Figure 69). Those analogies draw heavily on semantic and conceptual associations with the Nike brand (e.g., shoes for sports). Other sectors (e.g., industrial products, household electrical appliances, air conditioning, robots, containers, and real estate) were also verbalized.

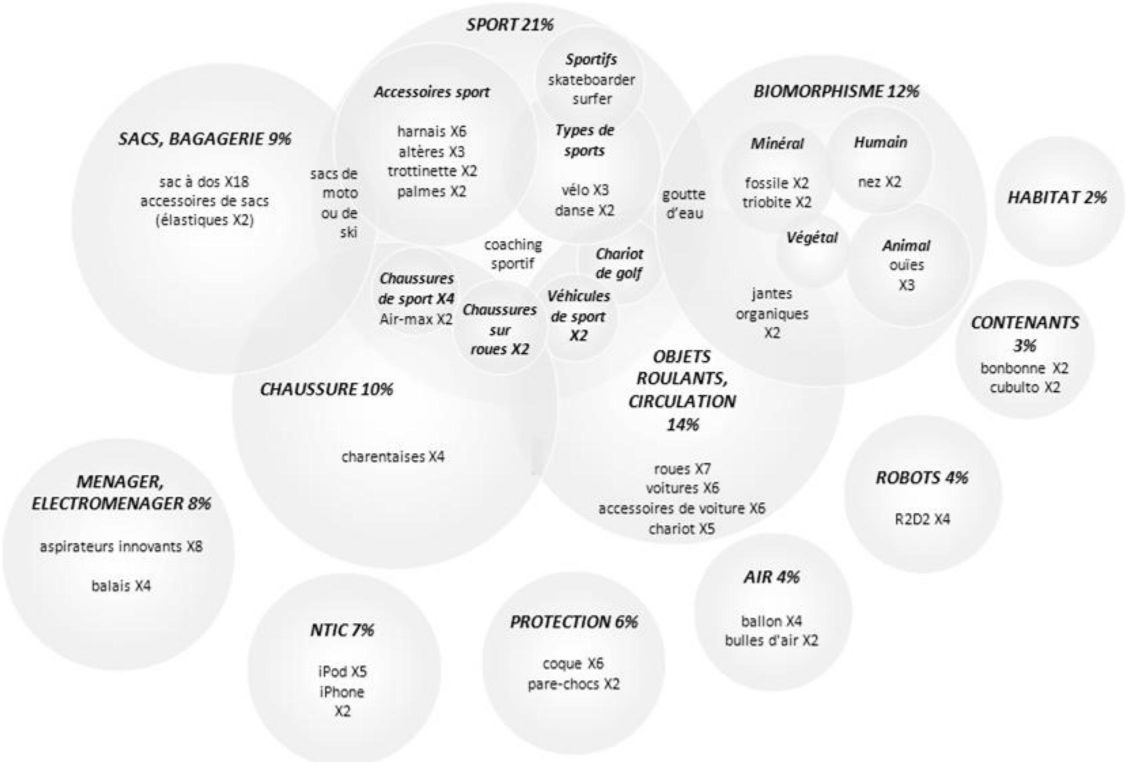


Figure 69. Sector of analogy (minimum two times cited in the experiment) (GENIUS D.7, 2009)

4.1.4.4 Cognitive operations during the mental categorization of information

Figure 70 shows the frequencies of different cognitive operations. On average, *association* accounted for 32.0% of all cognitive operations, *judgment/decision* accounted for 17.5%, *questioning* accounted for 16.0%, *transformation* accounted for 13.0%, *visuospatial attention* accounted for 11.9%, and *selective attention* accounted for 4.1%. During the generative phase, designers exerted relatively more effort to generate ideas by retrieving design information from memory; retrieval processes of all sorts *(association/ transformation/questioning)* accounted for 61.0% of all cognitive operations. Thus, judgment/decision was used less frequently than association. In addition*, selective attention* rarely inspired responses; because our experiment focused on memory-driven processes, we tried to eliminate external stimulation and encouraged designers to rely solely on their mind/memory during the task.

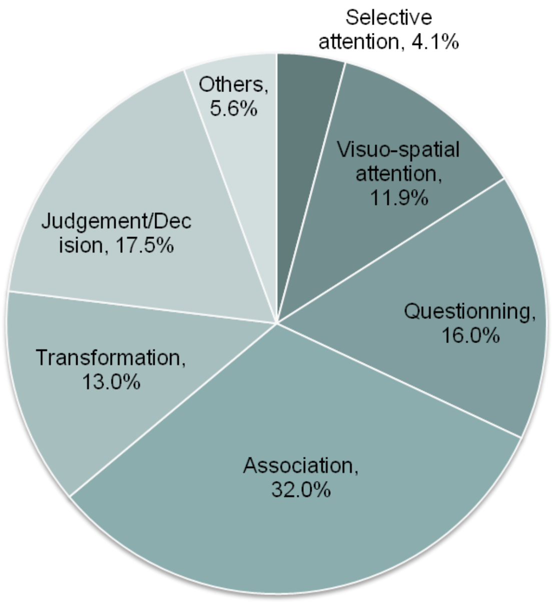


Figure 70. Frequencies of cognitive operations

Moreover, because cognitive operations related to retrieval processes were of great interest in this experiment, we intended to re-code the cognitive operations of ‘‘association’’ and ‘‘transformation’’ in terms of the subcategories of design information (cited in Table 9). According to the three levels of information, design information can be associated in three ways: descending association (from concrete to abstract), ascending association (from abstract to concrete), or same level of association.

- **Association & Transformation**

A more detailed analysis of the results showed that a plurality of the 32.0% of the responses accounted for by association were *same level of associations* (17.6%), i.e., links between functions (Mf–Mf), semantic descriptors (Hs–Hs), or sectors (Ms–Ms); this was followed by *ascending associations* (8.7%) and *descending associations* (6.7%). Figure 71 shows the frequencies of each subcategory of association. Most *ascending associations* involved the middle to the high-level (M→H), referring to links between functions and semantic descriptors (Mf–Hs); or the low to high-level (L→H), referring to links between descriptions of forms and semantic descriptors (Lf–Hs). Representative *descending associations* included the link between functions and descriptions of forms (Mf–Lf) or the use of words to form descriptions (Hs–Lf).

Using cognitive operations of *transformation*, designers created new and interesting ideas or concepts by forming analogies with functions (Mf–Ha, 45.9%) or by exploiting the meanings of words (Lf–Ha, 34.9%) (See Fig. 71). In section 5.2.1, the links between association and transformation will be discussed in greater depth and presented in a cognitive model of the mental categorization of information processing.

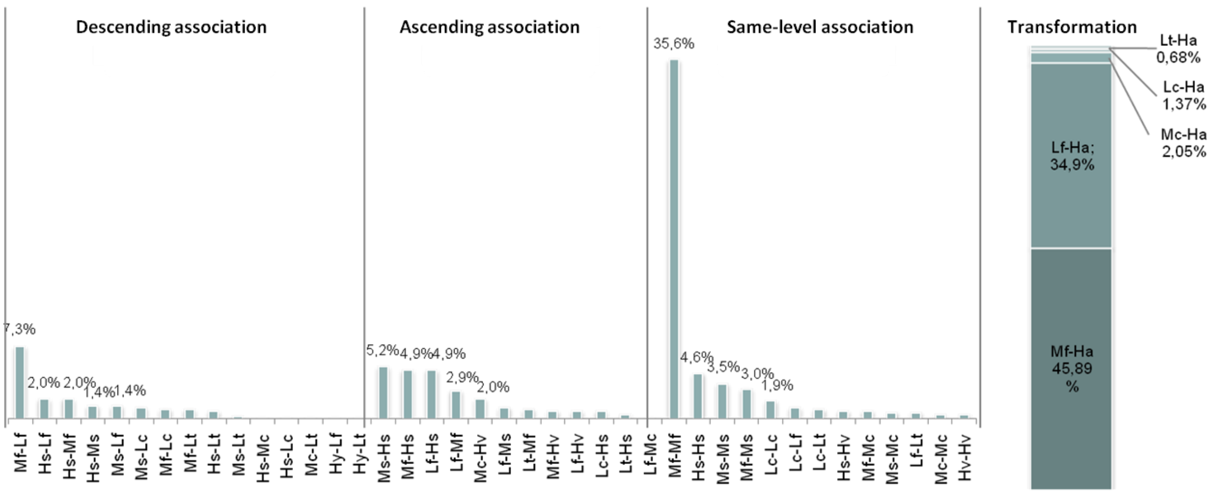


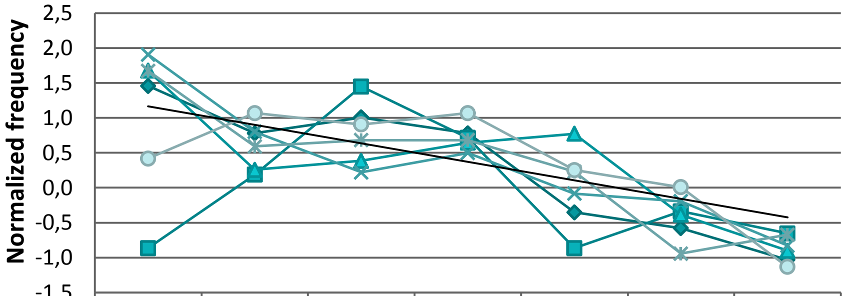
Figure 71. Frequencies of association and transformation operations by subcategory during the concurrent verbalization of 16 product designers

- **Changes in cognitive operations over time**

To compare changes in the six cognitive operations over time, we summed the number of cognitive operations in each 10-min interval. The normalized frequencies of cognitive operations were calculated as follows **(Bilda & Gero, 2007)**:

$$\left(\text{Normalized\_A} = \frac{\text{A} - \text{Mean}}{\text{Standard deviation}} \right)$$

Thus, if a cognitive operation increases in frequency, the normalized frequency will have a positive value, and if cognitive operations decrease in frequency, the normalized frequency will have a negative value. As illustrated in Figure 72, we observed two different groups of cognitive operations that shared a similar tendency. One group consisted of association, transformation, questioning, and selective attention and the other group consisted of visuospatial attention and judgment/decision. During the first 10 minutes, the only negative variance was observed for visuospatial attention; this may be attributable to the tendency of designers to rely more heavily on memories for retrieving mental information at the beginning of the design process. After a brief interval, the designers started externalizing their idea into early sketches to represent their ideas and/or identify errors. For this reason, the operation of judgment/decision resembles that of visuospatial attention.



	0-10 mins	10-20 mins	20-30 mins	30-40 mins	40-50 mins	50-60 mins	60-70 mins
Selective attention	1,5	0,8	1,0	0,8	-0,4	-0,6	-1,0
Visuospatial attention	-0,9	0,2	1,4	0,7	-0,9	-0,3	-0,7
Questioning	1,7	0,3	0,4	0,6	0,8	-0,4	-0,9
Association	1,9	0,8	0,2	0,5	-0,1	-0,2	-0,8
Transformation	1,7	0,6	0,7	0,7	0,2	-0,9	-0,7
Judgment/ Decision	0,4	1,1	0,9	1,1	0,3	0,0	-1,1

Figure 72. Normalized frequencies of each cognitive operation every 10 min during current verbalization of 16 designers

During the remainder of the observation, all variances tended toward negative, indicating that the designers' cognitive operations slowed after 40 minutes. However the variance was higher for visuospatial attention than for the other cognitive operations; that is, designers continued to improve their ideas by sketching or retouching the features of forms until they were satisfied with the outcomes.

- **Correlation between cognitive operations categories**

Lag Sequential Analysis (LSA) is a technique for analyzing quantitative data, in which the sequential order of the data is examined. It is traditionally used in the field of experimental psychology to study the behavior of person to person interaction (how often certain behavior is preceded or followed by other specific behavior) **(INTERACT, 2009)**. According to a method described by **Allison & Liker (1982),** and **Heller & Tanaka-Matsumi (1999),** z-scores greater than ± 1.96 ($p < 0.05$) indicate that observed frequencies exceeded base rate levels. A positive z-score means that the sequence is likely to occur at greater than base rate levels; a negative z-score indicates that the sequence is less likely to occur. The significant z-scores (more than ± 1.96) are shaded in Table 11.

Table 11. Z-Scores for cognitive operations

	Descending association	*Ascending association*	*Same level of association*	*Selective Attention*	*Judgment /decision*	*Visuospatial attention*	*Questioning*	*Silence*	*Transfor mation*	*Sum*
Descending association	0.54	0.39	0.53	-0.64	-0.06	-1.64	-1.21	2.02	-0.53	-0.6
Ascending association	-0.56	0.76	0.43	-0.71	-1.63	-0.49	0.08	-0.05	2.46	0.29
Same level of association	0.78	1.41	0.87	-0.34	-0.46	-2.26	0.11	1.16	-0.86	0.41
Selective Attention	-0.4	-0.69	-0.35	2.66	-0.46	-1.19	2.01	0.51	-0.62	1.47
Judgment decision	0.09	-0.61	-0.65	0.39	-1.64	2.21	-0.90	1.79	-0.09	0.59
Visuospatial attention	-0.58	-0.27	-1.90	-1.14	1.04	2.73	-1.75	1.94	-0.48	-0.41
Questioning	-0.6	0.93	-0,32	-1.15	-1.44	0.03	1.82	1.14	-0.08	0.33
Silence	0.33	0.42	1,55	-0.01	3.36	2.53	0.79	-7.09	-0.11	1.77
Transformati on	-0.37	-0.67	-0,11	-1.37	0.83	-1.41	0.19	1.04	1.35	-0.52
Sum	-0.77	1.67	0,05	-2.31	-0.46	0.51	1.14	2.46	1.04	3.33

Consistent with the results shown in Figure 72, the operation of judgment/decision and visuospatial attention have positive z-scores, which indicates positive interaction sequence of interest. They also have positive correlation when designers remain silent (non-verbalization). When designers associated design information from high-level to low-level information, designers also tend to remain silent.

In addition, after designers associated design information in ascending way (low-level→high-level), the cognitive operation of transformation was likely to occur. When they received *selective attention* through outer or inner senses, the cognitive operation of questioning was likely to happen. However, the operation of same level of association and visuospatial attention was less likely to occur sequentially.

4.1.4.5 Exploratory vocal and facial expressions

Table 12 shows a total number of vocal expressions used by 16 designers during generative phase. It should be noted that, 'verbal acknowledgement' was significantly used by designers in more than half of the verbal expressions. Interestingly, we observed a different tendency of vocal expressions used by both expert and novice designers. Expert designers tended to use affirmative words on the solution or the task itself, such as 'aha', 'oh yes', etc. when new information or idea occurred to designers. Then, 'surprise vocalization', 'laughter', and 'uncertainty' were followed. In case of novice designers, they tended to use vocal expressions in 'uncertainty' category, such as 'well', 'hmm', 'I don't know', next to 'verbal acknowledgement'.

Table 12. Total numbers of vocal expressions by 16 product designers (8 experts and 8 novices)

	Vocal expressions				
	Verbal acknowledgement	Surprise vocalization	Laughter	Uncertainty	Total
8 Experts	51	14	12	12	89
8 Novices	32	8	4	25	69
Total	83	22	16	37	158

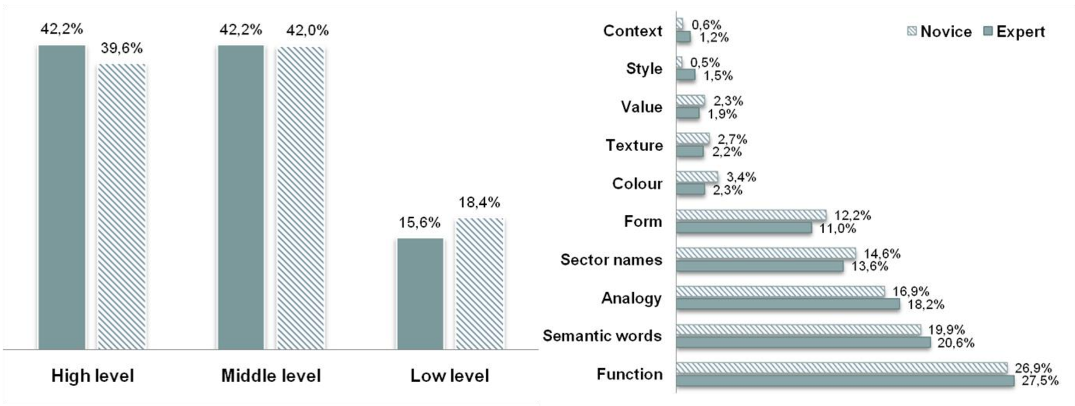
These results suggest that expert designers tended to use vocal expressions in affirmative way, and more often experienced surprise or amusement during the generative phase. In comparison, novice designers were careful to use affirmative words when they evaluate the outputs or the task itself. Therefore, instead of using 'verbal acknowledgement', novice designers have a significant tendency to use 'uncertainty' categories of vocal expressions.

Regarding facial expression of designers, as Figure 73 showed, we observed varied gesture and facial expressions of designers during the generative phase. However, it was very hard to quantify the results because designers lowered their head when they generate sketches or observe them most of the time.

Figure 73. Examples of gestures and facial expressions of designers

4.1.4.6 Differences between novice and expert designers in cognitive process

In this section, we aimed to identify differences between novice and expert designers in the cognitive process. First, the bar chart in Figure 74a shows the frequencies of types of design information. Comparing novice to expert designers for each category, different tendencies of percentages for design information were founded. Expert designers more often verbalized high- and middle-level information than novice designers. Novice designers tended to use relatively higher percentages of low-level information than expert designers did. According to the detailed frequencies of each category (See Figure 74b), design information related to function and semantic words have similar occurrence percentages in both novice and expert designers; however, the rest of categories were slightly different. In addition, two-way ANOVA test (without replication) was used to find the statistical significance between novices and experts. However, there is no significant difference ($p<0.05$) for frequencies of design information between them.



(a) *(b)*

Figure 74. Frequencies of each level of design information between novice and expert designers

Second, we compared the frequencies of cognitive operations between novice and expert designers. There are no significant differences in each cognitive operation from two-way ANOVA test

Last, the occurrence percentages of each cognitive operation of ‘’association’’ were compared between novice and expert designers (see Table 13). Both novice and expert designers highly associated design information between function ↔ function and function → form. However, except for cognitive operation of ‘’association’ from function to semantic words. This association was placed third for novice designers (6.3%); however, for expert designers, it was pushed back until 7th (3.3%). The rest of association, which placed high frequencies were the association between middle- and low-level information through semantic words in the both novice and expert designers.

Table 13. Frequencies of cognitive operation of ''association'' between novice and expert designers

	Total		*Expert*		*Novice*	
1	Function ↔Function	35.6%	Function ↔Function	33.0%	Function ↔Function	38.0%
2	Function →Form	7.3%	Function →Form	8.6%	Function →Form	6.6%
3	Sector name→ Semantic words	5.2%	Sector name→ Semantic words	6.2%	Function → Semantic words	6.3%
4	Function → Semantic words	4.9%	Form → Semantic words	5.1%	Semantic words ↔ Semantic words	5.0%
5	Form → Semantic words	4.9%	Semantic words ↔ Semantic words	4.0%	Form → Semantic words	4.7%
6	Semantic words ↔ Semantic words	4.6%	Sector name ↔ Sector name	4.0%	Sector name→ Semantic words	4.4%
7	Sector name ↔ Sector name	3.5%	Function → Semantic words	3.3%	Sector name ↔ Sector name	3.1%
8	Function ↔ Sector name	3.0%	Function ↔ Sector name	3.3%	Function ↔ Sector name	2.8%
9	Form → Function	2.9%	Semantic words → Form	3.3%	Form → Function	2.8%
10	Semantic words → Form	2.0%	Form → Function	2.9%	Context → Value	2.2%
-	Semantic words → Function	2.0%				
-	Context → Value	2.0%				

4.1.5 Discussion

4.1.5.1 Discussion of the results

- ***Information categorization***

In the early stages of the design process, designers used various levels of information in reducing abstraction through the integration of more and more constraints **(Bouchard et al., 2003, 2008)**. The results showed that sixteen designers (8 experts and 8 novices) naturally transformed and categorized different kind of levels and categories of design information during early sketching in the generative phase. In support of our previous work in modeling designer's informative phase **(Bouchard et al., 2008)**; the mental categorization of information would be based on the use of attributes from low-levels such as formal, chromatic, and textural ones to high-level descriptors. The high-level descriptors were often semantic adjectives, but other grammatical forms were also possible, such as the words used in Kansei dimensions as semantic, sensorial, emotional, context, and product attributes **(Schütte & Eklund, 2009).**

As Figure 68(a) shows, the portion of use of information level is quite similar between the designers (*Middle-level ≈ High-level* >> *Low-level*). Given that the use of high-level information to link words with images and vice-versa imposed a much greater cognitive load than low-level attributes **(Pasman, 2003)**, we observed that designers are able to use high-level information, especially *semantic words (Hs)* and *analogy (Hf).* Concerning the occurrence percentages of categories (Figure 68(b)), the most used categories, on average, were *function (Mf), semantic words (Hs), analogy (Hf), sector name (Ms), and form (Lf). Otherwise, style (Hy), context (Mc), texture (Lt), and color (Lc)* were relatively less verbalized.

In addition, we found that diverse tendency of using design information exists different between designers due to the differences of ages, sex, work experience, etc. Particularly, a significant use of high-level information (semantic words and analogies) can be interesting research topic because it may influence the creativity and emotional aspects of design.

- ***Cognitive operations***

Regarding cognitive operations of designers, we found that two representative cognitive operations: association and transformation, were particularly related to retrieval processes of mental information. The findings imply a cognitive mechanism about how mental information may be encoded and stored in long-term memory (LTM) and moved to working/short-term memory (WM/STM) during early sketching in the generative phase. In addition, the results from normalized frequencies of cognitive operations and sequential analysis have demonstrated a strong correlation between ‘‘*visuospatial attention*’’ and ‘‘*judgment/decision*’’ (See Figure 72 and Table 13). Both cognitive operations have also a positive correlation when designers remain silent. Given that our protocol analysis limited to only verbalized words, this correlation between specific cognitive operations and ‘‘silence’’ may enable us to understand the mental processes of designers and bridge the gap between explicit and implicit processes of designers. Moreover, since there were no significant differences in the rate of cognitive operations and the structure of design information between expert and novice designers, it implies that a cognitive process of designers can be modeled and applied to both expert and novice designers.

Furthermore, given that the notion of information level was initially derived from the field of artificial intelligence, where it is used to develop specific algorithms, the findings suggest that an explicit model may be helpful by developing a list of specifications for the development of computational tools. The development of system specifications is under way in section 5.3. They include the construction of databases (semantic descriptors, archetypes, divers analogy issued from different sectors), an association between design information, transformation of forms (morphing in terms of semantic descriptors, or analogy), a support of the memorizing process of design precedent, and so on.

- ***Affective processes of designers***

In order to identify emotional reaction of designers, which interplay with their cognitive processes, we collected and analyzed both linguistic and non-linguistic expressions. Especially, the latter seems very important in study of emotional reaction, because emotional reaction is hard to be expressed in a lexical way, and we could gather even a subtle reaction. In addition, some coincidental data could promise more reliable results.

Designers were naturally and intuitively conscious of emotional impact during cognitive processes to provide design solution, which is often characterized by its semantic expressions. It has been recognized that positive affect could play an important role in enhancing cognitive process **(Isen, 1999; Cabanac & Bonniot-Cabanac, 2007; Clore & Huntsinger, 2007, 2009)**. Especially, positive emotional spike, 'WOW effect' **(Hazlett & Benedek, 2007)** was observed in design practice when an individual is offered an experience by the product that is different from or more than what they expected. However, these studies initially addressed the affective values of product through the semantic attributes, or emotional reaction from users rather than designer himself **(Schütte, 2002; Bouchard et al., 2009)**.

In the perspective of measuring emotional response, the results from our protocol study without physiological measurement was insufficient and limited and they cannot provide continuous changes of emotional response. Thus, it is necessary to provide reliable physiological evidence to support our findings. The findings from our experiment can be a useful source to further hypothesize some factors of emotional impact on designer's cognitive process; moreover, it could be enriched with supporting literature reviews from psychology and neuroscience.

4.1.5.2 Limitations of current methods

- ***Effect of ''think-aloud'' method***

One might question whether designer's mental processes can be inferred from concurrent verbalization and/or whether sketching may be inhibited by the pressure of thinking aloud. Or some thoughts cannot be verbalized without causing a distortion in thinking **(Coley et al., 2007)**.

In our specific experiment, designers can naturally verbalize their thoughts and generate simultaneously sketches during more than half of the time (53.0%). Only for 23.8% of the protocol, designers remained silent. In addition, two pilot studies show that there are no significant differences in the production of sketches during the concurrent verbalization and non-verbalization condition. A similar approach has been carried by **Gero & Tang (2001)** and **Bilda (2006).** This result indicated that designers are generally capable of verbalizing when they generate sketches or take a note.

Interestingly, we found that there is significant differences between novice and expert designers in verbalizing and sketching simultaneously as pointed out in section 4.1.4.2., That is, according to their level of expertise, expert designer can better verbalize with simultaneous tasks (sketches or note) than novice designers can. These different cognitive abilities between novice and expert designers need to be further studied. In addition, we still assumed that inter-individual differences can be occurred due to age, sex, language, cultural differences, etc. For example, even though all participants in our experiment were French-speaking designers, 4 out of 16 designers do not speak French as a native language. Thus, non-native French speaking participants may feel uncomfortable with concurrent verbalization than native speakers may.

- ***Reliance on designer's own resources***

There are two concerns regarding the reliance on designer's own resources. The first one is that designers were asked to sketch without using external sources, although the information process in the traditional design activity is a crucial part of the design process **(Bouchard et al., 2006)**. In fact, sources of inspiration, and reference sectors are essential bases in design thinking, for defining design context, triggering idea generation, and structuring their mental representations **(Eckert & Stacey, 2000)**. However, the aim of experiment was to understand the mental categorization of information processing of designers in the generative phase. Thus, our experimental condition was specifically focused on the question about what kind of mental information is extracted from their memory solely and how it can be transformed or categorized during early sketching. Few expert designers and most novice designers have expressed their needs to bring some inspirational sources and/or refer to existing products. However, since they started to concentrate their idea flow, they adapted well to the experimental conditions. The reporting results were also various and rich in terms of applying *function* (Mf), *semantic words* (Hs), *analogy* (Ha), and *sector names* (Ms) (See Figure 68).

The second concern was about external stimulation due to the experimental environment. As we explained above, it was necessary to provide an environmental support to concentrate easily on a given task. That was the reason why the experiment was set up in their design agency in order to minimize uncertain variable/external stimulation from their natural working environment. However, we observed that designers tended to stop sketching and verbalizing, when their idea flow was blocked. Then, they looked around their environment and distracted their attention. Sometimes designers were also stimulated by certain situated objects. For example, once one designer (D8) watched the bicycle wheel in the experimental room, he sketched an object related to the form of bicycle with verbalizing *'I had seen the mini- sports shoes on the bicycle wheel in the show window'* (See Figure 75).

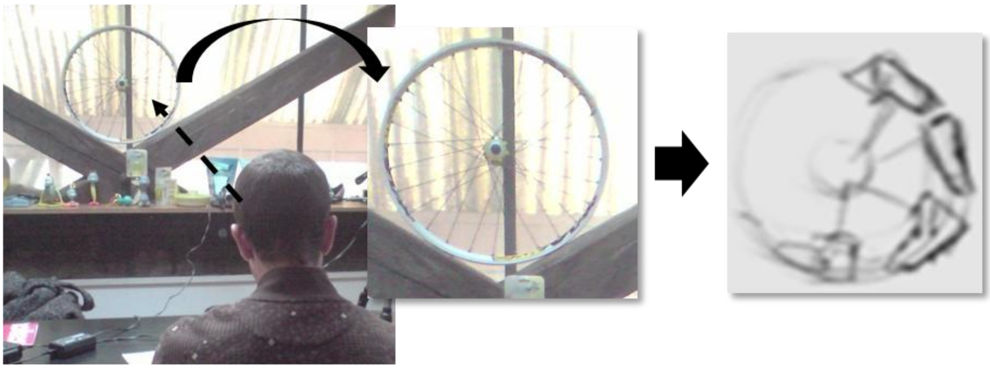


Figure 75. Examples of sketches due to the influence of external stimulus

4.1.5.3 Validation of HYP 1

HYP 1 and its sub-hypotheses were tested during EXP 1. HYP 1 concerns modeling cognitive and affective processes, whereby designer mentally categorize design information to further generate early sketches in the generative phase. HYP 1.1 concerned more cognitive processes of designers while HYP 1.2 was related to affective processes of designers (See Figure 76).

Concerning HYP 1.1, three types of results (qualitative, quantitative, and integrated) showed: (1) two representative cognitive operations, association, and transformation, were particularly related to retrieval processes of mental information. The findings explain a cognitive mechanism about how mental information may be encoded and stored in long-term memory (LTM) and moved to working/short-term memory (WM/STM). In addition, we have confirmed a strong correlation between the perception and the judgment/decision; (2) regarding the structure for design information, functional, and structural analogies as well as the links among functions, semantic descriptors, and descriptions of forms have emerged as an area of great interest.

Regarding HYP 1.2, we intended to identify whether emotional reactions of designers would interplay with their cognitive processes in generating stimuli and evaluating their results during the generative phase. In order to quantify them, we tried to combine physiological measurements with concurrent verbalization protocol. However, during pilot study 2, we found that it was hard to analyze physiological signals due to the specific experimental conditions (e.g. concurrent verbalization and sketching). Therefore, we analyzed vocal expressions of designers and gathered interesting qualitative results with some examples. However, the results from our protocol study without physiological measurements are insufficient and limited. Therefore, it should be necessary to integrate reliable physiological measurements. Further, both qualitative and quantitative approaches would enable to produce a rich model of cognitive and affective processes of designers, dedicated to the mental categorization of information processing.

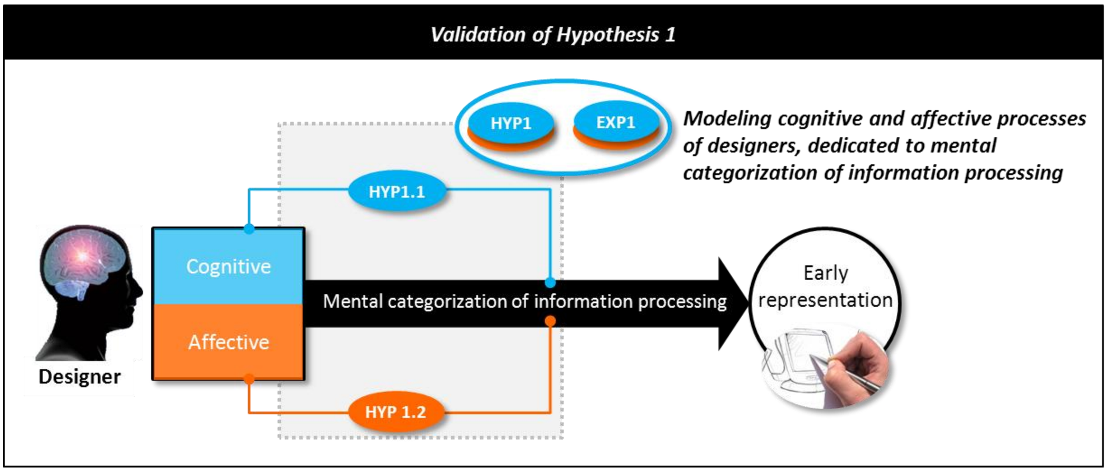


Figure 76. Validation of HYP 1

4.1.6 Conclusions of EXP 1

During EXP 1, we aimed to formalize cognitive and affective processes of designers, dedicated to mental categorization of information processing during the generative phase. The objectives were to quantify mental information and its cognitive operations dedicated to our specific phase; next, to explore affective processes of designers which would interplay with their cognitive processes in generating stimuli and evaluating their results during the generative phase; finally, to identify the similarities and differences between novice and expert designers.

EXP 1 contributed to develop a model of cognitive and affective processes of designers, dedicated to mental categorization of information processing in the generative phase (See chapter V). Given that there are no significant differences between expert and novice designers in the rate of cognitive operations and the structure of design information, our specific phase can be modeled and applied to both expert and novice designers.

Furthermore, given that the notion of information level was initially derived from the field of artificial intelligence, where it is used to develop specific algorithms, the findings suggest that our model would be translated into a list of specifications for the development of computational tools. The development of system specification is described in section 5.1.3.

4.2 EXP 2: Exploring emotional response to early representations (sketches)

4.2.1 Objectives

The aim of experiment 2 (EXP 2) was to explore emotional response to early representations (sketches). In the generative phase, designers start with mental information, so that early sketches are the first externalization of this mental information. Therefore, these early sketches, as to early representations, may play an important role in conveying designer's intent (semantic and emotional) and predicting a final product form (See Figure 77).

EXP 2 had two objectives. The first was to identify emotional response to early representations (sketches). The second objective was to quantify it by combining cognitive and physiological methods.

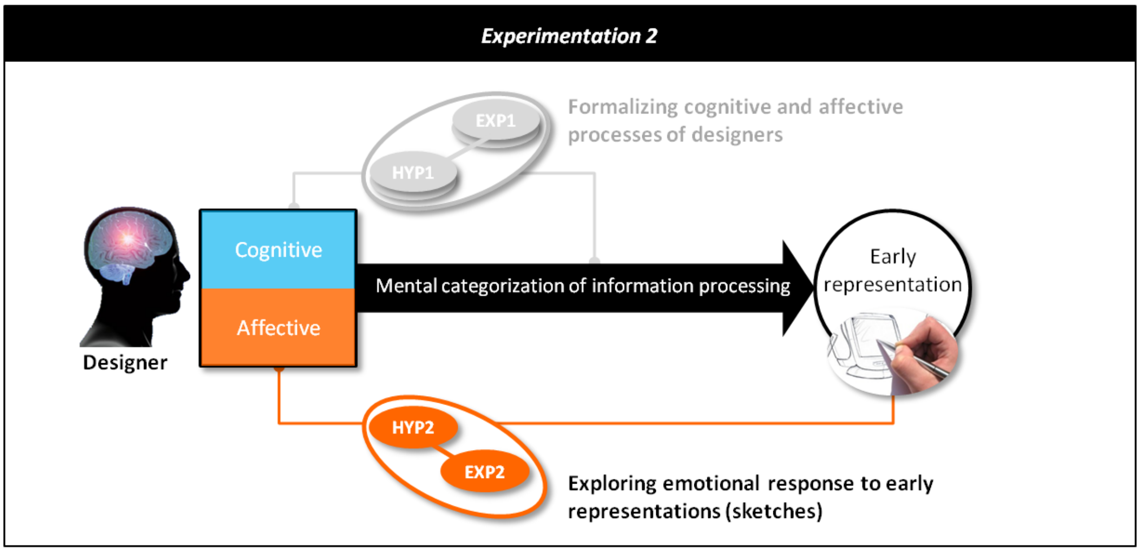


Figure 77. Positioning of EXP 2

4.2.2 Method

EXP 2 was designed to identify and quantify the emotional response to early sketches. In the field of emotional design and Kansei engineering, the cognitive method based on semantic differential approach has been extensively applied to assess the emotional response. Recent studies in Kansei engineering starts to triangulate cognitive methods with physiological ones such as Galvanic Skin Resistance (GSR), heart rate, and electroencephalography (EEG), etc.

During EXP 2, we intended to combine both cognitive and physiological methods to identify and quantify the emotional response to early sketches in design. All measurements derived are summarized in Figure 78. We expected that this combination of cognitive and physiological methods enable to measure subtle emotional states objectively, and also specify them with secondary emotion in a lexical way.

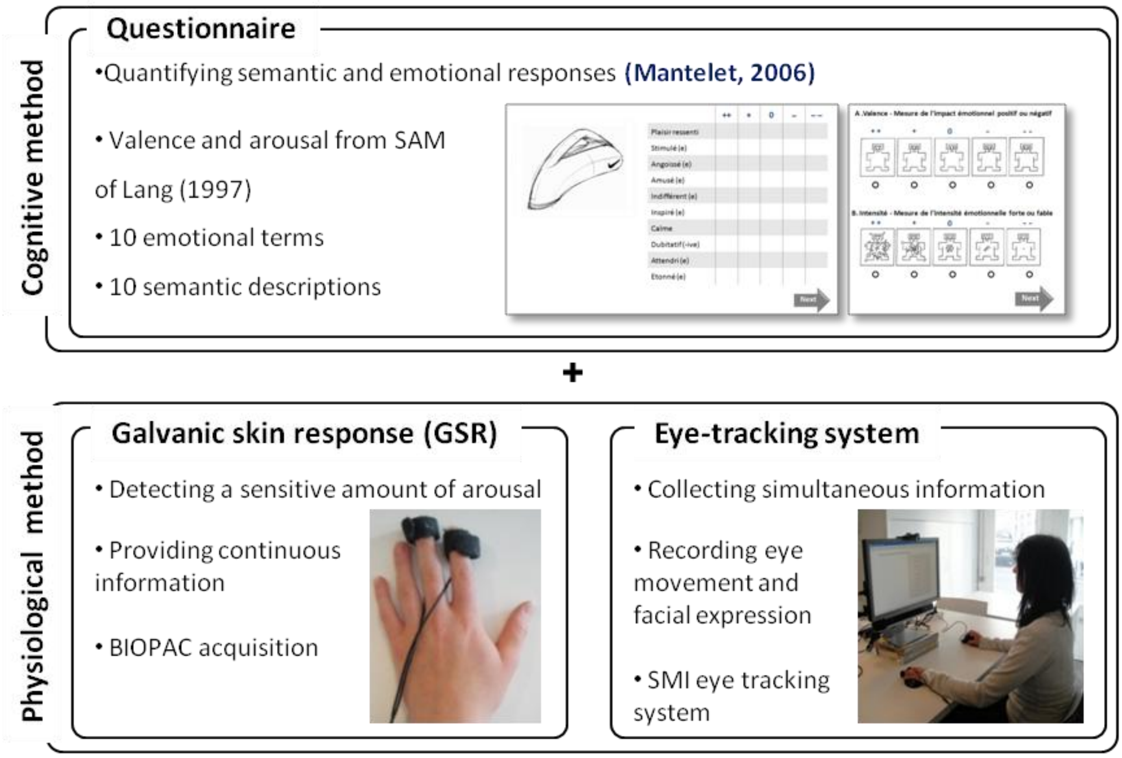


Figure 78. Summary of cognitive and physiological methods

4.2.1.1 Cognitive method: web questionnaire

Following a questionnaire developed by **Mantelet (2001)** to identify and quantify semantic and emotional response to trend boards and product images, we quantified emotional response to early sketches. The questionnaire consists of valence/arousal of the Self-Assessment Manikin (SAM), 5-point rating scales for semantic descriptions and emotional terms. We added a ranking test at the end of questionnaire.

- **Definition of the image stimulus**

We gathered sixteen sketches resulted in EXP 1. The criteria for selecting sketches were the finishing quality and expressivity of the given design brief ''Nike vacuum cleaner''. Figure 79 shows ten sketches selected for EXP 2. All images stimuli were presented to participants in grey scale with a resolution of 1024x768. Under highly controlled conditions, participants could concentrate on the given images so that we could minimize other possible interruptions, including chromatic effect and experimental environment, etc.

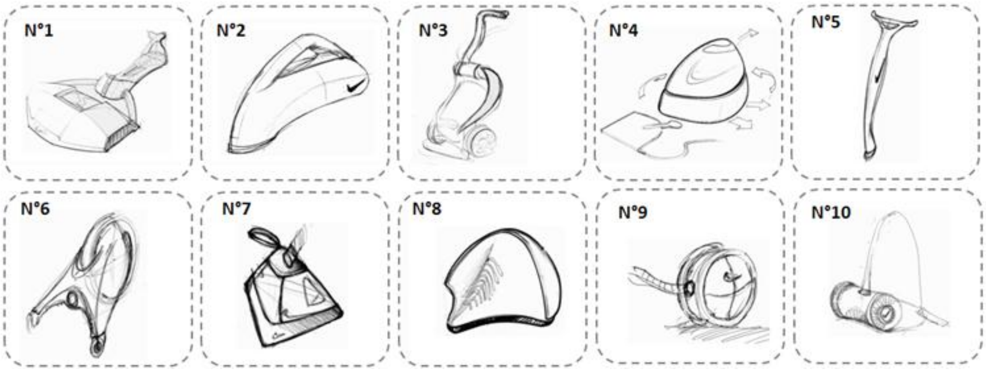


Figure 79. Ten sketches selected for image stimuli

- ***Definition of the lexical corpus (emotions, semantic adjectives)***

The Self-Assessment Manikin (SAM) scales by **Lang (1997)** were employed in terms of valence (positive or negative feelings) and arousal (intensity of emotions) using five pictorial images.

The list of 10 emotional terms and 10 semantic descriptions to be rated on 5-point rating scales (from 1 = ''not at all'' to 5 = ''very much'') each. Emotional terms, which reflect secondary emotions, are relatively hard to verbalize in a lexical way. Thus, we prepared a list of 20 emotional terms extracted from **Geneva Emotion Research Group (1998)** along with emotional terms verbalized by designers during EXP 1. Following a similar protocol, we gathered the most verbalized semantic words during EXP 1. Finally, two expert designers selected the ten most pertinent emotional terms for our specific experiment (see Table 14)

Table 14. List of emotional terms and semantic descriptions for EXP 2

10 emotional terms	*10 semantic descriptions*
amused(amusé),	organic (organique),
stimulated (stimulé),	appealing (sympatique),
afraid (apeuré),	intelligent (intelligent),
enthusiastic (enthousiasme),	light (léger),
hesitant (hésitant),	sportive (sportif),
ill at ease (mal à l'aise),	masculine (masculine),
passionate (passionné),	modern (moderne),
serene (serein),	rapid (rapide),
surprised (supris),	dynamic (dynamique),
impressed (impressionné).	rigid (rigide).

- ***Definition of a ranking test***

A ranking test assessed by asking them to rate the given early sketches in a rank order. Considering that it may be difficult for judges to rank a large number of sketches, participants were asked to rank the top three sketches from 1 to 3 (ranking 1 = ''most pertinent''). Open-ended questions about their choices were posed later on.

4.1.2.2 Physiological method: Galvanic skin conductance (GSR) and eye-tracking system

During EXP 2, selecting physiological measurements was essential to detect emotional response elicited by early representations (sketches), which may express a subtle emotional response. In addition, it was necessary to synchronize the both cognitive and physiological results. Therefore, our criteria for determining physiological measurements were non-obstructiveness of natural behavior, easy interpretation of signals, and high reliability of data. Finally, we applied a GSR and an eye-tracking system at the same time.

- ***Integration of Galvanic skin response (GSR) system***

A significant advantage of GSR is that it can provide continuous information and detect very sensitive amount of arousal **(Tran et al., 2007; Ganglbauer et al., 2009)**. In order to employ GSR, the two GSR electrodes were placed on two fingers of the left hand. Changes in the skin conductance were collected at 200Hz per second. Using the BIOPAC acquisition unit and the software BSLPro 3.7, we could amplify the collected signal and visualize it (See Figure 80).

(a) (b) (c)

Figure 80. (a) GSR SS3L cable, (b) BIOPAC-MP36: acquisition, (c) BSLPro 3.7 software (BIOPAC, 2010)

- ***Integration of an eye tracking system***

The first aim for using eye-tracking system was to synchronize the results from web-based questionnaire and physiological results. Thus, eye-tracking system concurrently records a screen capture video of all actions, which the participants perform when operating the web-based questionnaire application. This method enables to record automated input time in questionnaire, so that physiological data could be synchronized with questionnaires.

(a) (b)

Figure 81. (a) SMI eye tracking system, (b) Begaze software (SMI, 2010)

In addition, during the task, we expected to collect physiological phenomenon gathered from eye tracking system such as fixation number/duration, pupil size, and blink rate/duration in order to provide robust results with those from GSR measures. An analysis of the physiological data from eye tracking is underway; we put it into our perspectives of the thesis (→ Section 6.2.1). That is the reason why we categorize an eye tracking system as a physiological measurement.

4.1.2.3 Participants

A total of six master degree product designers in our laboratory took part in a pilot study. They were five women and one man. They were all French students. During the main experiment, we recruited twelve designers, which consisted of six master degree product designers (novices) and six expert product designers (seven women and five men). The average years of work experience of six expert designers was 9.2 years. The age of these subjects ranged from 23 to 41 years of age (average age = 29.4).

4.1.2.4 Procedure

The questionnaire consisted of three slides: preparation, stimuli, and rating.

- **The Preparation slide** is a blank page in order for the participants to relax and stabilize their emotional state before watching the next stimuli slide.
- **The Stimuli slide** holds each image stimulus chosen in Figure 79.
- **The Rating slide** consisted of three types of questions as described previously.
  - The Self-Assessment Manikin (SAM)
  - The list of 10 emotional terms to be rated on 5-point rating scales
  - The list of 10 semantic descriptions to be rated on 5-point rating scales

Following Lang's method **(Lang, 1997)**, each test began with a preparation slide that lasted 5 seconds. Then, a stimuli slide was presented for 6 seconds. Finally, the participants were asked to fill in a questionnaire in rating slide. On the rating slide, a small thumbnail image was displayed for helping the designer's evaluation process. The 11s loops (Preparation slide → Stimuli slide) were the same for each image stimulus. Once rating slide was over, the computerized preparation slide was then activated until all images stimuli were rated. At the end of the experiment, participants were asked to rank the top three sketches from 1 to 3, among ten sketches being the most pertinent to the design brief ''Nike vacuum cleaner'' (See Figure 82).

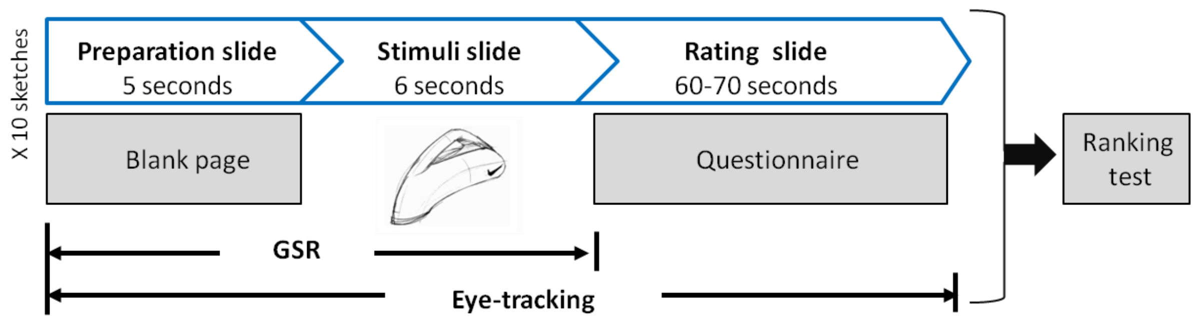


Figure 82. Procedure of EXP 2

4.1.2.5 Data gathering and analysis

- **Data from questionnaire**

Principal Component Analysis (PCA) was used to reduce and quantify multidimensional data sets from the questionnaires **(Mantelet, 2006; Bouchard et al., 2008; Nagamachi et al., 2008)**. The aim was to identify semantic and emotional response to early representations (sketches). We used specific statistical analysis program ''Statbox'' for this analysis **(Grimmersoft, 2010)**.

- **Data from a Galvanic skin response (GSR)**

As Figure 82 shows, the most interesting GSR values were their changes during the preparation and stimuli slides. Therefore, we first segmented the GSR values for 11 seconds each by using Biopro 3.7 software **(BIOPAC, 2010)**. Next, as large inter-individual differences were expected, we normalized the GSR values [0, 1] each using the following formula:

$$\left(\text{Normalized\_GSR} = \frac{\text{Original\_GSR}}{\text{max\_GSR}} \right)$$

Finally, we calculated the average of this normalized GSR values of 12 participants. The result is visualized in graphics to compare the change of GSR values between preparation and stimuli slides. (→ section 4.2.3.4)

- **Data from eye tracking system**

We gathered a focus map from **Begaze^{TM}2 software (SMI, 2010)** (See Figure 81b). With the focus map, gaze patterns are visualized by altering the transparency of the stimulus display based on the amount of attention received. A number of fixation hits related to brightness between darkest (less hits) and normal brightness (more hits). Many researchers used 'heat map' for the same reason; however, we intended to visualize gaze patterns with focus map in order to highlight the focused area with brightness.

4.1.2.6 Pilot study and protocol validation

- **Objectives**

The objective of the pilot study was to evaluate the performance of combined cognitive and physiological measurements. We expected that animal and product images might contain much greater emotional impact than sketches, and may be easier for detecting emotional response. Thus, we conducted this study with animal and product images.

- **Protocol**

We gathered six sets of inspirational animal source and corresponding car images (see Figure 83). The criteria for selecting image stimuli were the name of vehicle and the similarity to animal body posture selected by designers. The colored images were then treated so that they could be presented in the most homogenous way (grey scale, size, resolution, etc.).

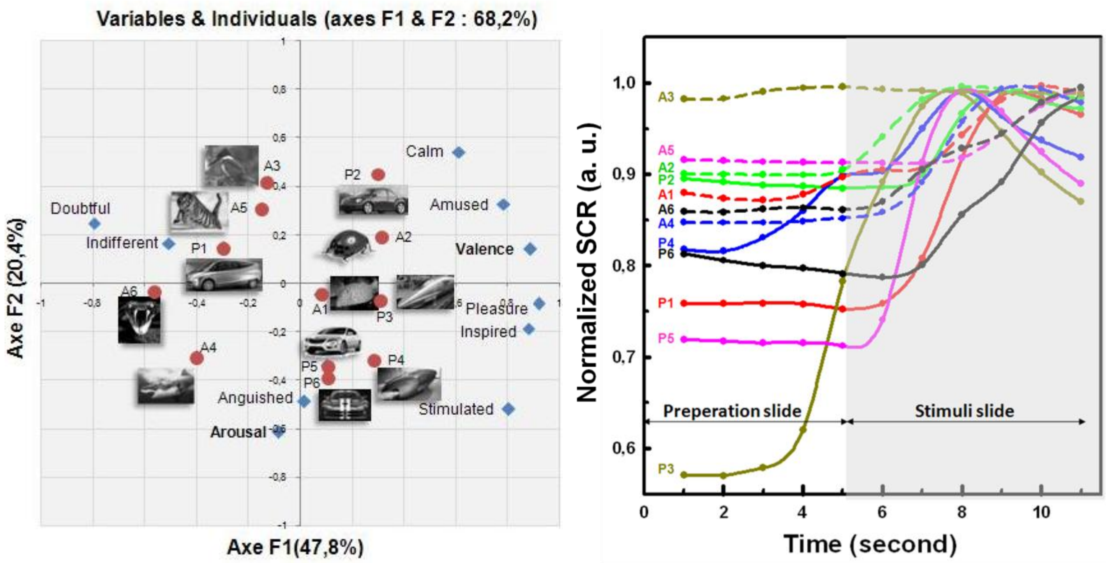
Figure 83. Inspirational animal source and corresponding car design (Kim et al., 2010b)

The four designers were asked to provide the emotional terms elicited in the same set of images. Since emotional terms which reflect secondary emotion are relatively hard to express in a lexical way, a lists of 20 emotional terms extracted from **Geneva Emotion Research Group, (1998)** was made available to the designers during the annotation process. The retained emotional terms were: *amused, calm, pleasure, inspired, stimulated, anguished, indifferent, doubtful, astonished, and tender.*

For the main test, we recruited six novice designers in LCPI. They were divided in two groups: one group was to rate inspirational source (A1~A6); the other was to rate product image (P1~A6).

- **Results and protocol validation**

In order to identify the correlation between emotional terms, we applied a principal component analysis (PCA) of emotional terms on the inspirational source image and product image (see Figure 84a). The contributions of factors were focused on Factor 1 (20.4%) and Factor 2 (47.8%). These two factors can explain 68.2% of the data. The principal axes were confirmed *positive-negative valence* and *high-low arousal.* Figure 84b showed the normalized average GSR value for 11 seconds: 5 seconds for the preparation slide and 6 seconds for the stimuli slide as indicated respectively by the white and grey region of the image. This graph employed the same color code for the paired images. A dotted line represents animal images (A1−A6) and a continuous line represents the product images (P1−P6).



(a) *(b)*

Figure 84. a. PCA of emotional terms for animal images and corresponding product images; b. Change of the normalized average GSR for 11 seconds

Given that galvanic skin response (GSR) measure skin conductivity responses (SCR), which usually associated with arousal, we were interested in the peak and troughs of SCR (Figure 84b). The normalized average SCR started at low-level in preparation slide; however, SCR data suddenly increased and showed a peak in stimuli slide (common latency of rise was 1-3s). The paired images A4-P4 and A6-P6 have showed relatively high arousal values in PCA sphere. This was consistent with the results in which SCR has high augmentation of amplitude tendency. In comparison, A2-P2 had a low arousal value in PCA, and amplitude augmentations were also small. In addition, we analyzed a similar tendency of GSR data in time between paired-images (animal – product) in case of A2-P2, A4-P4, and A6-P6 images; however, in the rest of cases, it was hard to explain the correlation of GSR data, including A1-P1, A3-P3, and A5-P5. In summary, we can conclude that a correlation between PCA results and SCR exists in terms of emotional response with some limitations. Thus, our protocol can be exploitable for the main experiment. Nevertheless, identifying emotions elicited in sketches and quantifying them is still a challenging work. Based on these finding, we conducted the main experiments with 12 designers. The results and discussion are described in section 4.2.3 and 4.2.4.

4.2.3 Results

In this section, the qualitative and quantitative results are presented in five subsections:

- Ranking analysis → §section 4.2.3.1
- Principal Component Analysis (PCA) of semantic descriptions in sketches → §section 4.2.3.2
- PCA analysis of emotional response in sketches →§section 4.2.3.3
- Change of skin conductance response from sketches→§section 4.2.3.4
- Visualization of eye gaze data using focus maps →§section 4.2.3.5

4.2.3.1 Ranking analysis

Figure 85 showed the sum of the ranking points with weighted ranking values. We assigned points from 1 to 3 according to a ranking, for example, ranking 1 = 3 points, ranking 2 = 2 points, and ranking 3 = 1 point. Both the quantitative and qualitative analysis have been conducted.

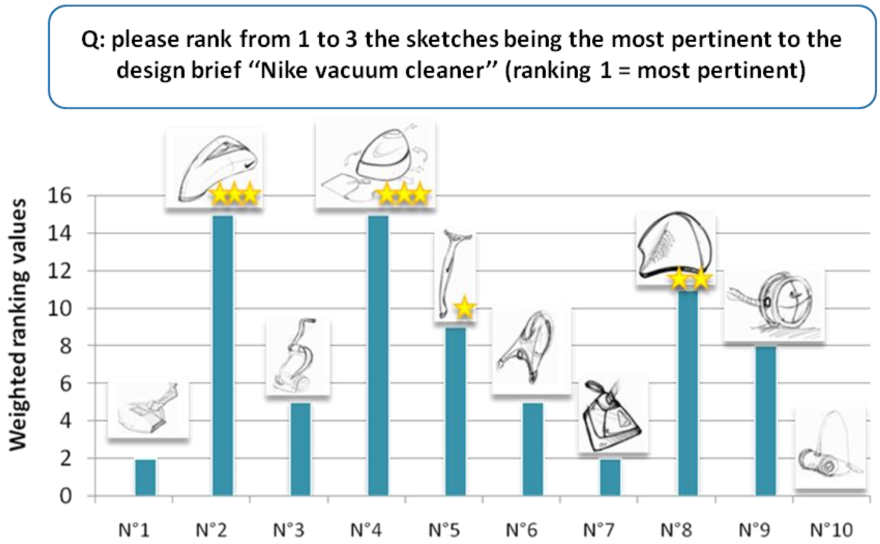


Figure 85. Ranking analysis

(1) The N4 and N2 got the highest score. The N8 and N5 were the 2nd and 3rd highest ones. Relatively, the N9, N6, N3, N1, and N7 were less scored by participants. None of the participants selected the N10. (2) The participants who had ranked as the N4 first, had not selected the N2 for the second ranking (except for D7) and vice-versa. The result implied that those sketches were perceived differently by participants and had distinct features to express 'Nike vacuum cleaner' (3) The participants who ranked as ''1'' the N4 were all expert designers. None of the novice ranked the sketch N4 first. Given that we had six expert designers in the test, the ranking responses by expert designers were highly convergent. On the other hand, novice designers ranked the sketches in

a highly divergent way. Apparently, each novice designer ranked different sketches first, ranging from the N2, N3, N5, to N8; only two novice designers have commonly ranked the N9 first.

4.2.3.2 Principal Component Analysis (PCA) of semantic descriptions in sketches

We applied PCA analysis of semantic descriptions in Nike vacuum cleaner sketches. Semantic assessment aimed to identify the correlation between semantic responses and to define the "ideal" vision of 'Nike vacuum cleaner' in terms of semantic descriptions.

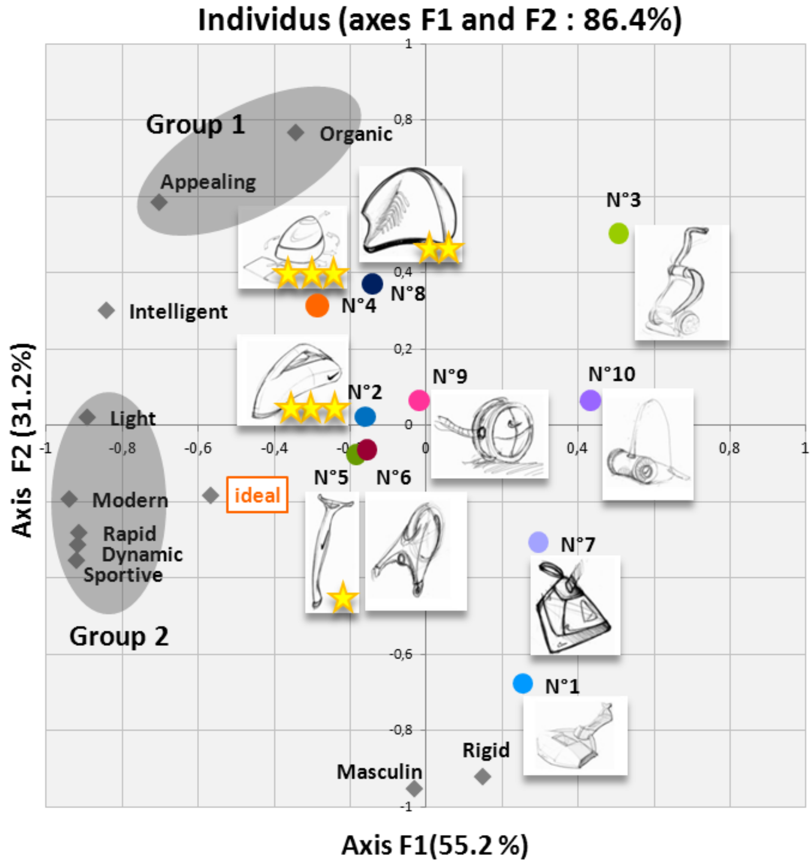


Figure 86. PCA of semantic descriptions of Nike vacuum cleaner sketches

Figure 86 shows the position of ten semantic descriptions, ten sketches, and the "ideal" vision in the extracted principal component sphere. Note that the "ideal" vision was not an item that we showed to the participants; the participants had created the "ideal" vision for Nike vacuum cleaner in their minds at the beginning of the experiment without any reference sketches. The semantic descriptions of the "ideal" vision gave us a reference for the evaluation of other sketches. We applied a color code for sketches (circle), and visualize a ranking with star symbols, for example, ranking 1 = 3 stars, ranking 2 = 2 stars, and ranking 3 = 1 star, as the same for Figure 86—88.

Given that cumulative contribution of PCA shows the correlation between semantic descriptions, the contributions were focused on F1 (55.2%) and F2 (31.2%), totally 86.4% for two principal factors. They had two groups of semantic descriptions as follows:

- Semantic group 1 : modern, rapid, dynamic, sportive, and light
- Semantic group 2 : appealing and organic

The results showed that the group 1 was closed to the “ideal” vision of Nike vacuum cleaner; group 2 was more distant.

4.2.3.3 Principal Component Analysis (PCA) of emotional response in sketches

According to PCA analysis of emotional response to early sketches in Figure 87, the contributions of PCA sphere were 89.3% for two factors (F1 and F2).

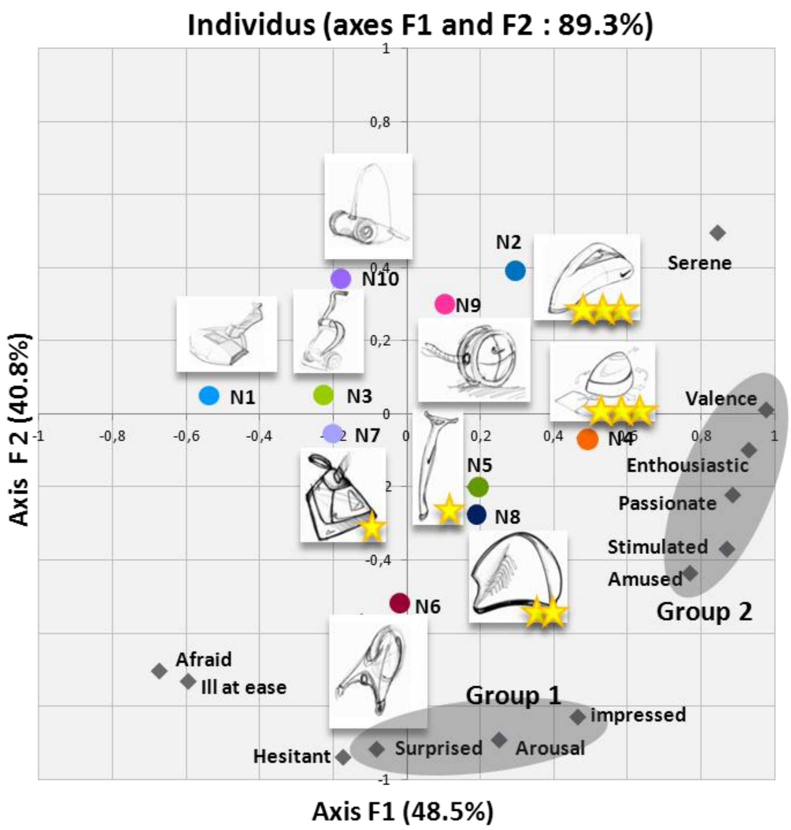


Figure 87. PCA of emotional terms of Nike vacuum cleaner sketches

The principal axes were confirmed positive-negative valence and high-low arousal. The positive valence reflected some complementary emotions, including enthusiastic, passionate, stimulated and amused. High arousal was related to impressed and surprised.

- Emotional group 1: positive valence (enthusiastic, passionate, stimulated, and amused)
- Emotional group 2: high arousal (impressed and surprised)

Both N4 and N2 ranked as ''1'' were positioned in highly positive valence axis. High arousal ratings were assigned to the N6, N8, and N5. Relatively, The N2, N10, and N9 received lower arousal ratings. Possible correlation between amplitude augmentation of skin conductance and PCA results will be discussed in section 4.2.3.4.

4.2.3.4 Change of skin conductance response from sketches

The galvanic skin response (GSR) sensor measured skin conductance response (SCR), which usually associated with arousal. Figure 88 shows the normalized average skin conductance during 11 seconds (5 seconds for the preparation slide and 6 seconds for the stimuli slide as indicated in dotted line). The reason for the normalization of data was due to inter-individual differences in SCL latency and rise time **(Dawson et al. 2000).**

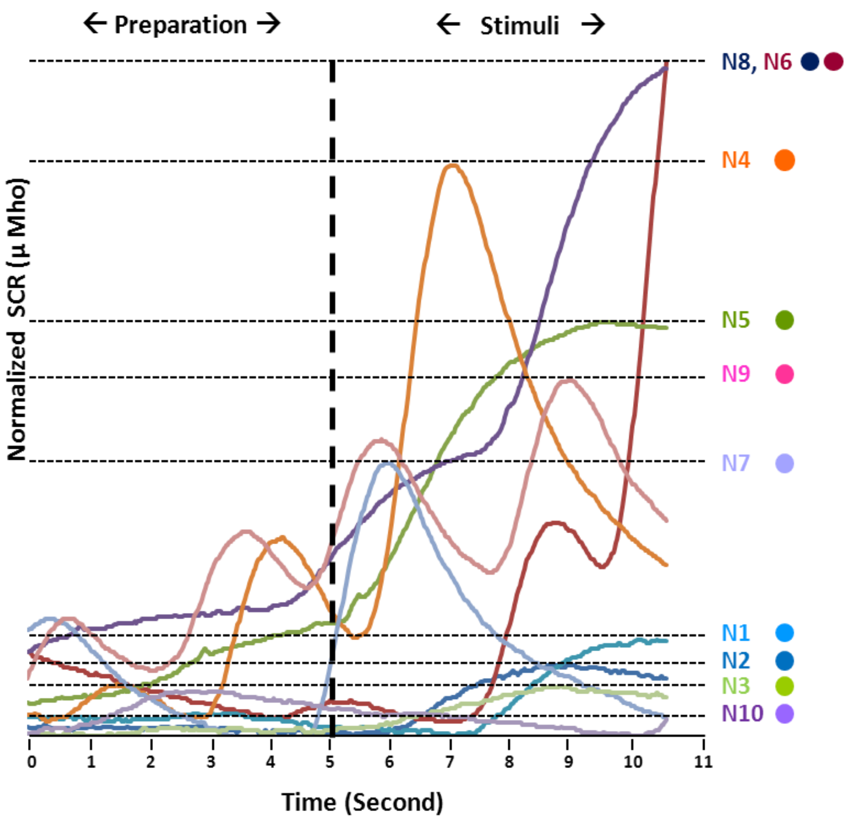


Figure 88. Change of the average of normalized skin conductance response (SCR) during 11 seconds

Figure 88 employed the same color code for the sketches as illustrated in Figure 86 and 87. As we explained our pilot study, we are interested in the peak and troughs of SCR. SCR has a tendency to increase, and shows a peak in stimuli side in most of the images. For the N8, N6, N4, N5, N9, and N7 (in order), we can interpret that they elicited higher emotional arousal. On the other hand the N1, N2, N3, and N10 did not show remarkable changes between preparation and stimuli slides, in other words, they elicited lower emotional arousal.

4.2.3.5 Visualization of eye gaze data using focus maps

By using Begaze™2 software **(SMI, 2010)**, we gathered the gaze patterns and a number of fixation hits. Traditionally, 'heat map' has been often used to visualize eye gaze data; however, color mapping tended to hide details of the stimulus image and caused difficulties during its analysis. Therefore, we employed the modified technique of visualization developed by **Spakov and Miniotas (2007)**. Based on the focus map, we added transparency on each focus map provided by 12 participants, and then they were overlaid. As a results, a number of fixation hits was related to the level of brightness between dimness (less hits) and brightness (more hits).

From the collected focus maps in Figure 89, we found that participants commonly looked at the given early sketches in discontinues way. The relative intensity of the participant's attention represented a specific interesting area of the image. Especially, designers have commonly paid attention to Nike logo. Their fixation area was quite converged in representing parts or lines.

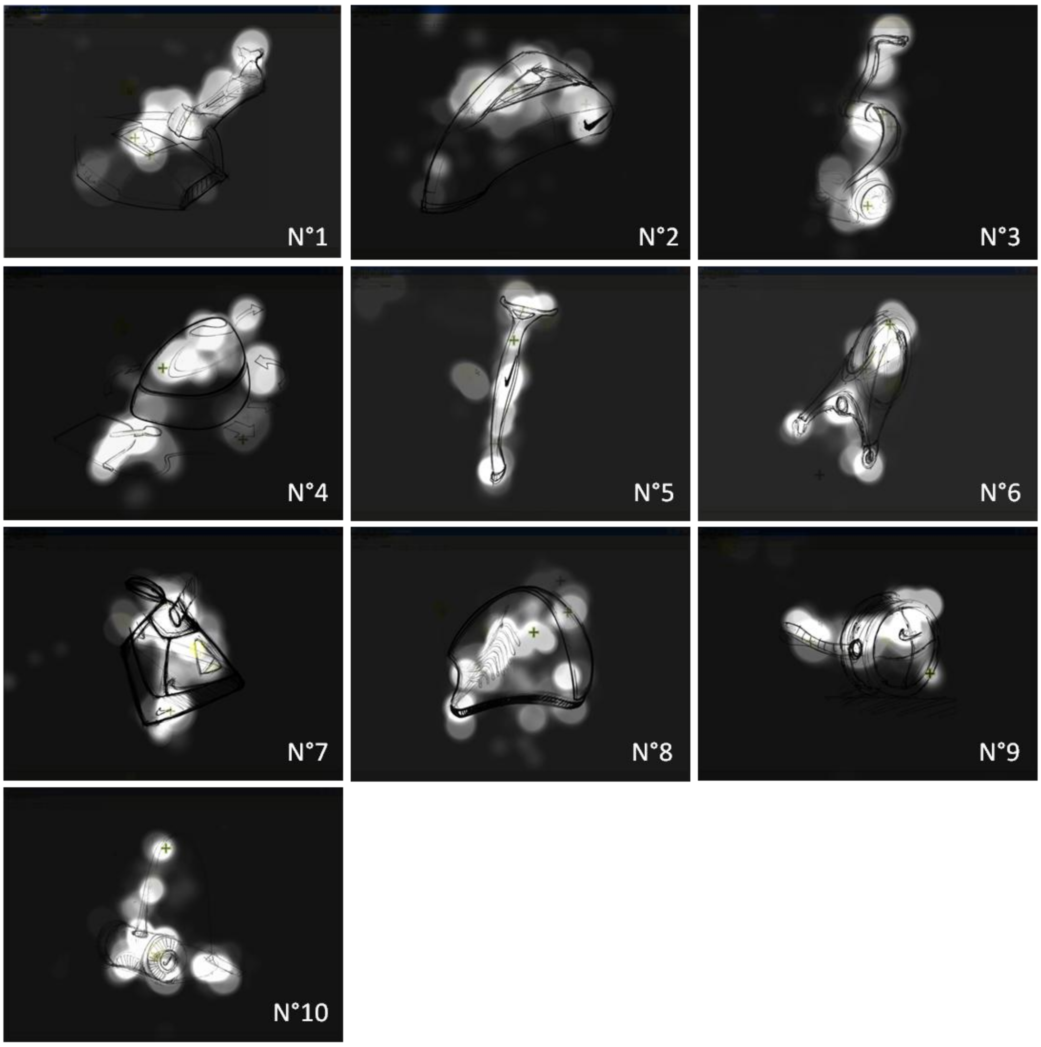


Figure 89. Eye gaze data using focus maps

4.2.4 Discussion

4.2.4.1 Correlation between semantic and emotional responses

In order to identify semantic and emotional response in early sketches, Principal Component Analysis (PCA) was used with semantic descriptions and emotional terms. In addition, ranking analysis was used to strengthen the cognitive results.

According to PCA analysis of semantic descriptions in sketches in Figure 86, we can conclude that the sketches N2, N5 and N6 were more representative for the semantic group 1 (modern, rapid, dynamic, and sportive), while the sketches N4 and N8 were more representative for the semantic group 2 (appealing and organic). Those two groups of early sketches were conformed to the previous results from ranking analysis. In section 4.2.3.1, we assumed that the sketches N2 and N4 that were rated as ‘’1’’, but expressed different semantic responses because who had rated N2 first did not selected N4 for second ranking and vice-versa (except for one out of 12 participants).

Regarding the PCA analysis of emotional response in sketches in Figure 87, both sketches N2 and N4 elicited positive feelings. Positive-valence state corresponded to secondary emotions, including enthusiastic, passionate, stimulated, and amused. In addition, we found that the top three ranked sketches (except for N2) have strong tendency to be positioned in right sides, which corresponded to positive valence.

In summary, PCA analysis of semantic and emotional response and a ranking analysis allowed us to identify semantic and emotional response to early sketches including the both primary and secondary emotions. It seems that early sketches are capable to express semantic features, and good early sketches may elicit positive feelings and high arousal state.

4.2.4.2 Correlation between the results from cognitive and physiological methods

Emotional response elicited by early sketches was analyzed using Principal Component Analysis (PCA) and changing Skin Conductance Response (SCR). We found a positive correlation between PCA results and skin conductance in the arousal dimension. According to Figure 87 and Figure 88, both results showed that the N8, N6, and N4 elicited relatively higher emotional arousal; N1, N2, N3, and N10 elicited relatively lower emotional arousal. In case of the rest image stimuli, including N5, N7, and N9, it was hard to interpret their correlation.

These results were consistent with earlier findings from the work of **Mahlke & Minge (2008)**. They found positive correlation between the arousal of Self Assessment Manikin (SAM) and changes of SCR.

The originality of our research resided in a validation of the correlation between the arousal of SAM and changes of SCR in design with specific stimuli: ‘‘early sketches’’. Given that early sketches might be hard to elicit emotion rather than other images having multidimensional attributes, we quantified their emotional response using physiological method and specified them with secondary emotional terms using a cognitive method.

4.2.4.3 Limitations of current method

- **Effect of using web-based questionnaire**

During EXP 2, we employed a web-based questionnaire instead of paper-based one. A web-based method enables us to count participant’s responses automatically so that we can reduce the time for gathering the data, and improve the reliability of the results. In addition, by recording screen capture video from eye-tracking system, we can also synchronize the event from questionnaire with GSR measures.

However, it seems that the use of web-based questionnaire might influence the results related to emotional state of designers. It is because designers are very sensitive to sketches on the paper rather than on the screen. For example, during ‘ranking’ test at the end of experiment, 10 sketches were printed in a single paper in order to compare them at a glance. Some designers were commented that they felt differently when they watched the image stimuli on a screen.

According to comparative study between a paper-based and a web-based questionnaire done by **Hardré et al. (2007),** a paper-based questionnaire may contribute to enhance data quality, and perhaps provide positive engagement than web-based questionnaires. Considering that most designers generate early sketches by traditional materials in their workspaces, the scanned sketches in digital format express differently, and their engagements can be also influenced.

In addition, the presenting image size was all unified in screen size (1024*768 resolutions), which led to a lack of consideration on the actual size of the product. The sketches described various types of vacuum cleaners: small hand-held types (N2, N5), robotic types (N4, N7, and N8), an upright type (N3), canister types (N6, N9, and N10), and other (N1). We assumed that relatively big size vacuum cleaner, such as an upright type and a canister type cannot sufficiently express their own semantic and emotional attributes comparing to small size vacuum cleaners. This finding confirmed that small-size vacuum cleaners, including hand-held type (N2, N5), robotic types (N4, N7, N8), are a relatively high correlation in terms of semantic and emotional response.

- **Combining different physiological parameters to increase reliability of the results**

During EXP 2, we intended to use GSR measures and eye tracking system as for physiological methods. The results from GSR showed positive correlation of results with questionnaires. However, GSR measures have detected only high-low arousal states; it is necessary to combine other physiological parameters to increase reliability of the results and to interpret a very subtle emotional state. For example, **Mahlke & Minge (2008)** have found that electromyography (EMG) was also highly correlated with the arousal of Self Assessment Manikin (SAM). Especially, EMG responses from the zygomaticus major were correlated with valence of SAM.

Regarding the eye tracking system, the data analysis is underway to gather two types of results: one is related to cognitive behavior on the image, including gaze pattern, and fixation region. The other is significant index related to physiological responses, including pupil diameter and blink rate/duration, etc.

Along with those two physiological methods, several physiological measurements exist to detect specific emotional or cognitive states as we presented in sections 2.3.2. Thus, to deepen our study, further study is intended to combine multi-physiological methods under careful considerations.

4.2.4.4 Validation of HYP 2

Hypothesis 2 (HYP 2) and its sub-hypotheses (HYP 2.1 and HYP 2.2) were tested during EXP 2. HYP 2 concerns the formalization of emotional response to early sketches to predict their emotional dimension from the early stages of the design process (See Figure 90).

Regarding HYP 2.1, the Principal Component Analysis (PCA) of semantic and emotional response and a ranking analysis allowed us to identify semantic and emotional response to early sketches including both primary and secondary emotions. We concluded that early sketches were capable to express their semantic feature. Moreover, good sketches can elicit a positive feelings and a high-arousal state. →HYP 2.1.

Concerning HYP 2.2, the correlation of results between cognitive method (questionnaire) and physiological method (GSR) allowed us to quantify emotional response to early sketches. The cognitive method specified primary emotion with secondary emotions elicited by early sketches, while physiological methods detected continuous and unconscious emotional state, which is reliable to quantify. →HYP 2.2.

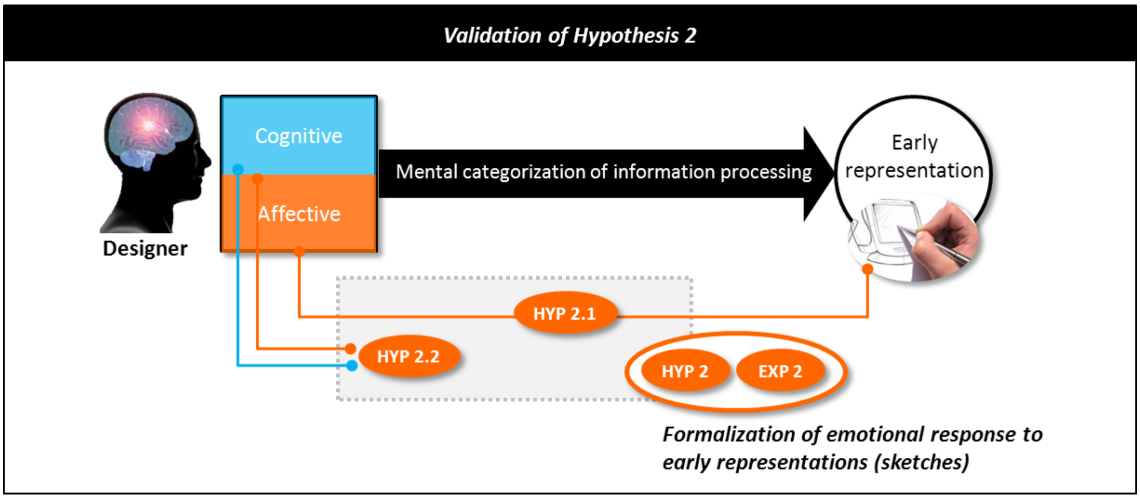


Figure 90. Validation of HYP 2

4.2.5 Conclusions of EXP 2

During EXP 2, we aimed to explore emotional response to early representations (sketches). In order to identify and quantify this emotional response to early sketches, we combined cognitive and physiological methods. Cognitive methods consisted of questionnaire (valence/ arousal of SAM, semantic descriptions and emotional terms, and ranking test). Physiological methods were Galvanic Skin Responses (GSR) and eye tracking system.

Based on our experiment, emotional response elicited by early sketches were identified and quantified. The results confirmed that early sketches are capable to express semantic features, and ''good form'' of early sketches may elicit positive feelings and high arousal state. It implied that we may predict emotions from early representations, and designer's intent (semantic and emotional) can meet with emotional response of consumers from the early stages of design. An emotional link can be established between early sketches and final products. Moreover, given that early sketches might be hard to elicit emotions rather than other images having multidimensional attributes, we combined cognitive and physiological method to quantify this emotional response to early sketches. This combination enables to measure an emotional state objectively, and specify them with secondary emotional terms.

Further study must be done to validate a combination of cognitive and physiological methods in other types of design information in earlier phases of the design process. For example, the emotional link from inspirational sources, early sketches, to final products can be of great interest. This issue will be discussed in more detail in section 5.2.

4.3 Synthesis of experiments

In chapter IV, we conducted two experiments (EXP 1 and EXP 2) with experts and novices designers in the product design domain. The experiments enabled us to bring cognitive and affective processes of designers, and its relationship with early representations (sketches) together (See Figure 91).

EXP 1 concerned cognitive and emotional aspects of design during mental categorization of information processing, while EXP 2 focused on the relationship between emotional aspects of design and its representations underlying our specific phase. Subsequent analysis finally yielded a model depicting the mental categorization of information processing performed by designers.

Based on the three types of results (qualitative, quantitative and integrated), we derived a model depicting the mental categorization of design information processing in the generative phase in the following chapter V.

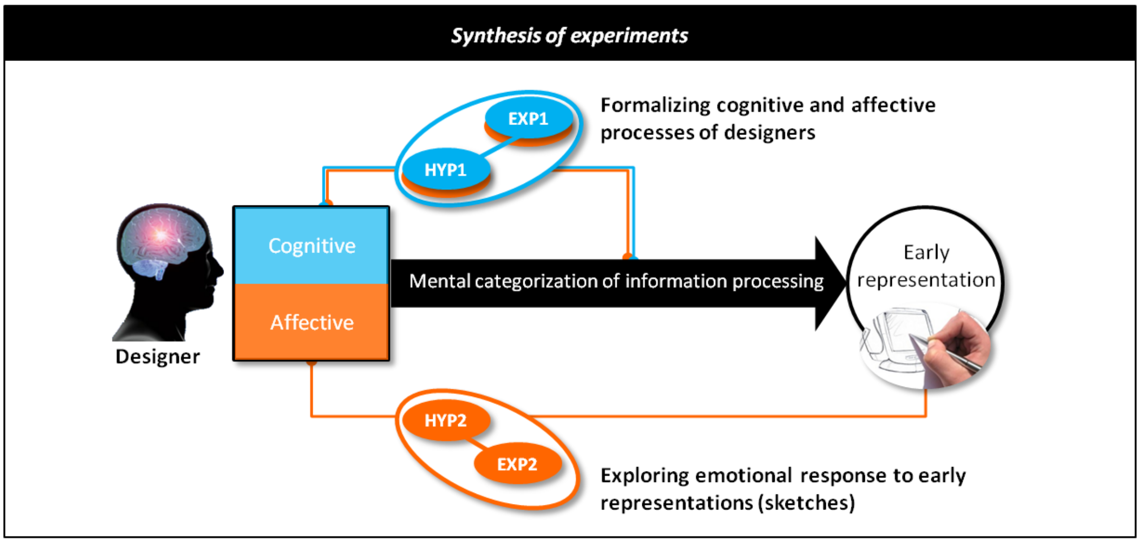


Figure 91. Synthesis of experiments

V. MODELING COGNITIVE AND AFFECTIVE PROCESSES OF DESIGNERS IN THE GENERATIVE PHASE

Introduction

Chapter V presents our key contributions based on the results from the empirical studies conducted in chapter IV. During EXP1 and EXP2, we intended to identify the kind of cognitive operations that extract design information from memory and to determine how this design information is transformed or categorized during early sketching. Both quantitative and qualitative approaches were integrated to produce a model depicting the mental categorization of design information processing performed by designers.

This chapter consists of four sections (See Figure 92). The first two sections propose a specific model depicting the mental categorization of information processing performed by designers in the generative phase (§5.1 and §5.2). The third section suggests a list of specifications for developing a computational tool dedicated to the generative phase (§5.3). Finally, this chapter concludes by summarizing contributions of the study in the perspectives of both scientific and industrial communities (§5.4).

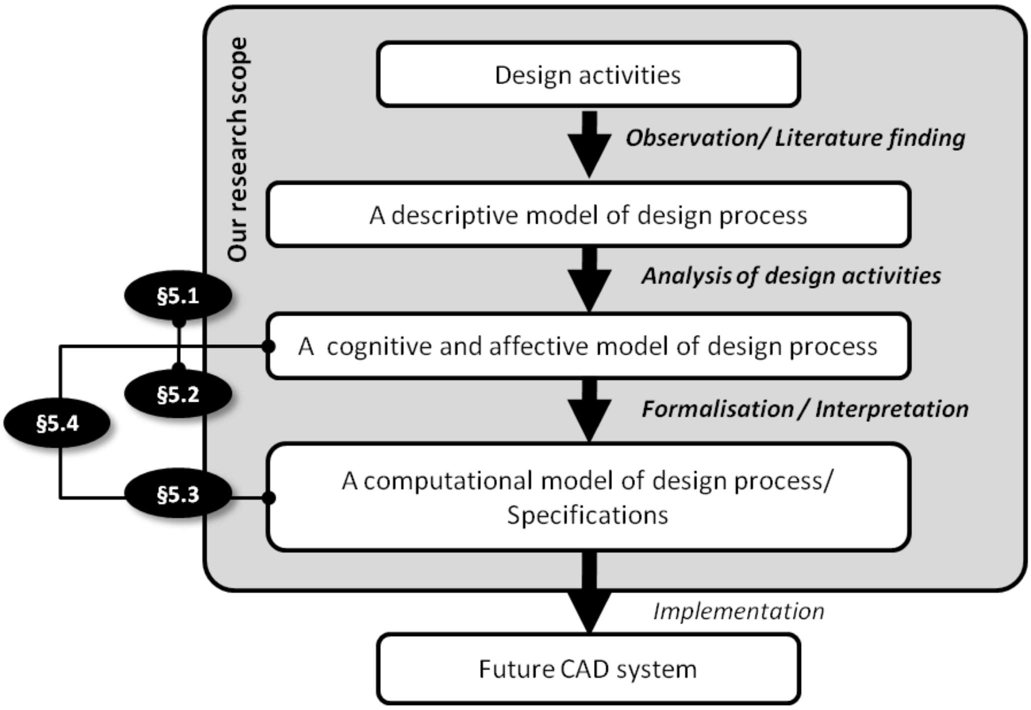


Figure 92. Structure of chapter V

5.1 A cognitive model of the mental categorization of information processing

In this section, we present a cognitive model of the mental categorization of design information processing performed by designers. This model is focused specifically on the structure of design information and two cognitive operations, association and transformation, which are representative of cognitive operations related to long-term and working memory. These provide clues to help us identify how designers encode and store information in long-term memory.

As Figure 93 illustrates, the solid lines represent the direction of association, and the dotted lines represent the direction of transformation. The width of the line indicates the frequency with which cognitive operations were performed on design information. The structure of design information is represented in the boxes. The size of boxes reflects the frequencies of particular types of as percentages of all verbal responses on the protocol study (→EXP1).

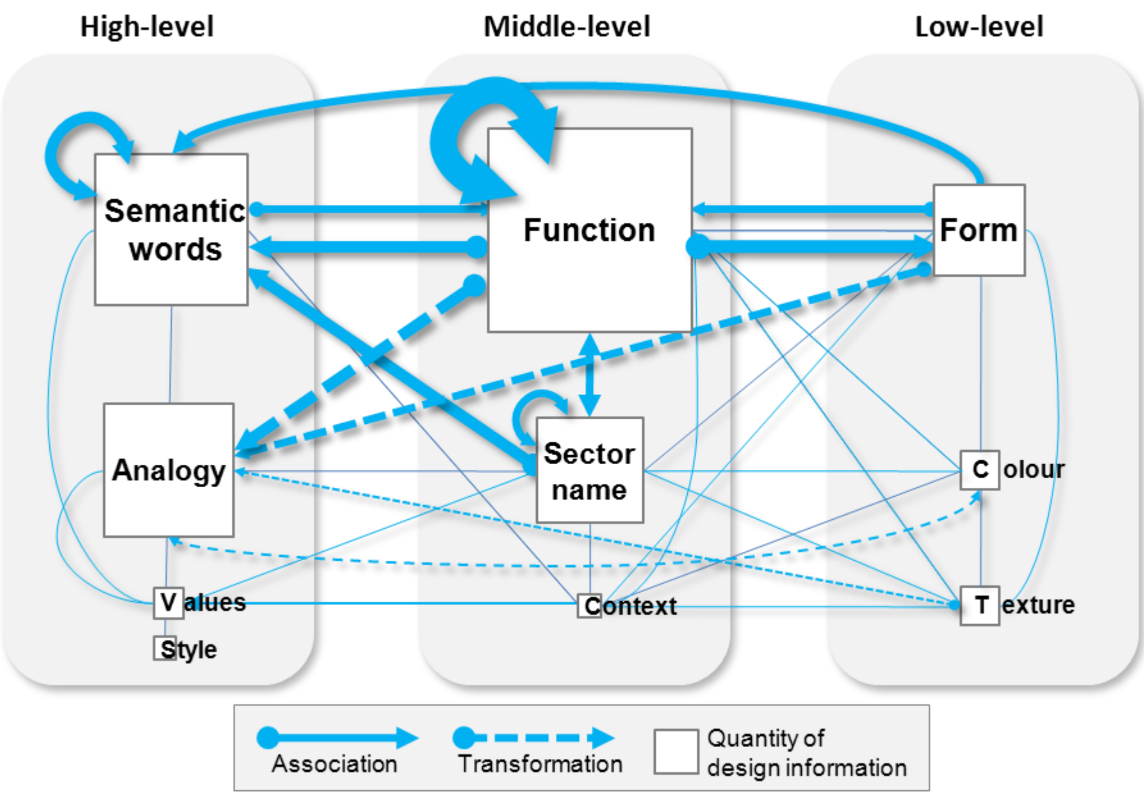


Figure 93. Structure of mental information and their cognitive links: association and transformation

The predominant forms of design information involve functions, semantic words, analogy, sector name, and descriptions of forms. Designers tend to use same level of associations among elements of design information (horizontal), especially between functions, pieces of semantic words, sectors. Some excerpts from the verbalizations are given as follows: *"I'll try a backpack type of vacuum cleaners. This model should provide enough power, but it should not be too heavy to carry on his shoulder. Also, I would guess that a potable battery-powered model will still be a problem. It is due that a wrong position of air evacuation could cause a person to heat up";* or *"I would like to start with an automatic vacuum cleaner, ah yes, like a robot, which has a technical aspect, like 'hi-tech'; and has a look more masculine, seductive, and aerodynamic"*

Remarkably, designers often associate information across different levels (vertical) including between functions and descriptions of forms, functions and semantic words, semantic words and descriptions of forms, and semantic words and sector names (and vice versa). Here are a few excerpts from the verbalization: *"regarding color ranges, sport colors in my head are very flashy, vivid, and dynamic. So I could use primary colors: red, green, blue, or yellow with a black accessory; and it could be better if I use glossy materials such as plastics, metal."*

Regarding the transformation of information by analogy, designers incline to imagine new relationship from completed independent of the object, especially, the functions and sector names. For example, *"Nike vacuum cleaner, Nike makes me imagine a form like a Capricorns' horn which might be more rounded…''.*

This model also states that the designers tend to associate design information according to rules that span different levels of information and relate colors, textures, and shapes. In addition to transformation, high-level descriptors (values, semantic words, etc.) may also use as sources of creativity in designing insofar as these descriptors reflect the designers' personal sensibilities and tendency to create designs based on divergent ideas. Thus, the bi-directional associative links between high- and low-level information constitute a very interesting focus for research on the generative phase performed by designers.

5.2 A model of cognitive and affective processes of designers in the generative phase

Figure 94 shows a model of cognitive and affective processes of designers in the generative phase. This model consists of two cycles that are the mental categorization of information processing and early sketching in the generative phase. Those cycles evolve by categorizing mentally design information and externalizing early sketches. It explains a constructive memory between mental information and early representations (sketches) as described in a model of ''seeing-drawing-seeing'' developed by **Schön & Wiggins (1992).**

A blue line indicates the cognitive process of designers in the generative phase. An orange line describes the affective processes of designers, which jointly influence their cognitive process. In addition, each blue circle represents a cognitive operation involved in the mental categorization of information processing and early sketching in the generative phase. The circle size illustrates the intensity of the use of cognitive operations that were quantified during the verbalization protocol. The dotted circles are considered as essential cognitive operations dedicated to our specific cognitive processing. However, they are not explicit due to their natural modality used by designer.

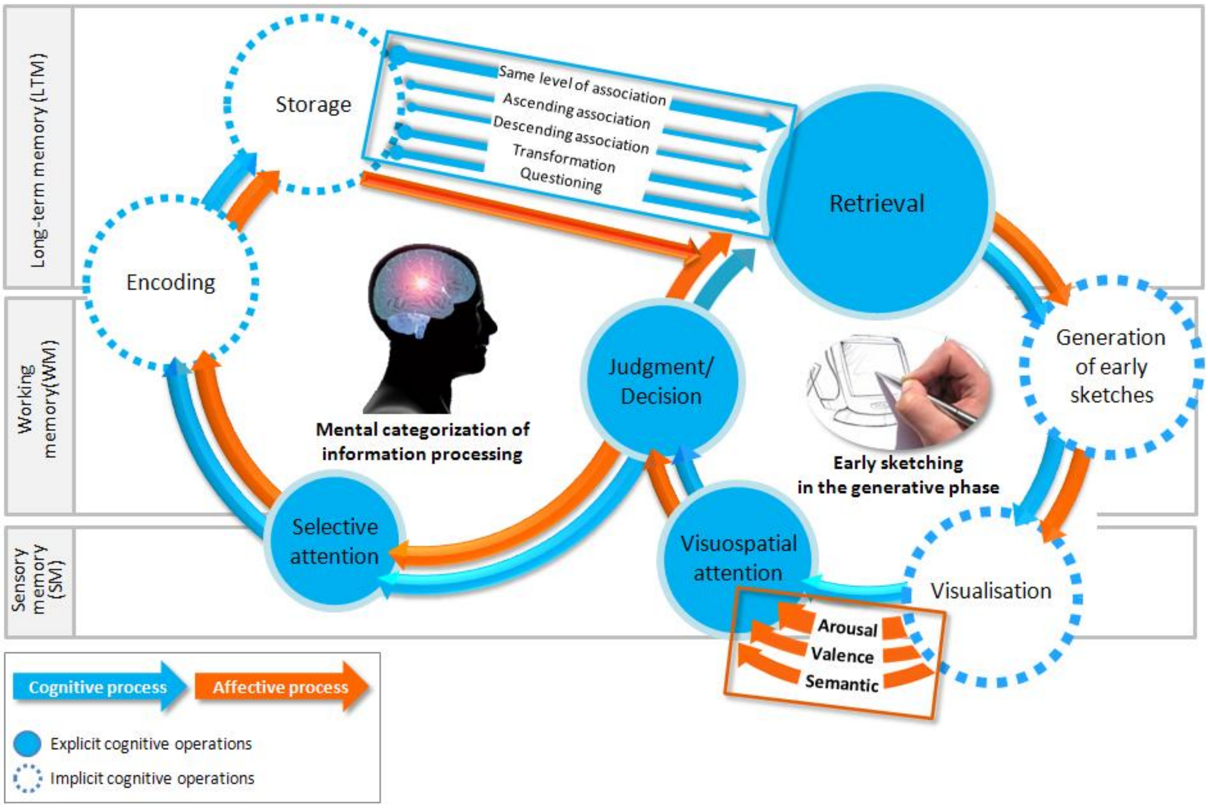


Figure 94. A model of the cognitive and affective processes of designers, dedicated to the generative phase

This model was initially based on a descriptive model of information processing that integrates memory models derived from cognitive psychology, described in section 3.2.1.1. They specifically described the transfer of mental information through memory (sensory memory (SM), working/short-term memory (WM/STM), and long-term memory (LTM)), and synthetize the mechanisms of different cognitive operations involved: those of **Broadbent (1958), Atkinson & Shiffrin (1968), Baddeley et al. (2009).** In general, the information process in design begins with 'external stimuli', which is referred to as 'bottom up process' (stimuli-driven). However, since our study was focused on a top-down process, which is driven by memory rather than by external stimuli, designers makes an effort to retrieve the number of mental information from their memory. During the experiment, it was necessary to minimize external stimuli under a controlled environment. That is the reason why the circle size of 'selective attention' is relatively small in our model. However, as we discussed in section 4.1.3.5, selective attention through outer sense is a natural cognitive operation during designing **(Style, 2005)**. For example, when designers experienced discontinuities in the flow of ideas or found design task difficult to accomplish, they tended to stop sketching and/or verbalizing; then tried to distract attention while looking around their environment. The retrieval process of mental information involves three types of cognitive operations: *associations (same level, ascending, descending)*, *transformation*, and *questioning*. As the size of the arrow illustrates the use of memory retrieval: *association/ transformation/ questioning* covered 66.7% of the total number of cognitive operations, as we expected. Especially *association* and *transformation* covered more than half of the total number of cognitive operations. Designers tended to associate mental information among the same level of information, especially between function-function, semantic words-semantic words, function-sector name and sector name-context. Designers also associate mental information in crossing different level of information, such as function-form description, function-semantic words and semantic words – form description and vice versa. In the case of *transformation*, designers tend to make an analogy with middle-level information (function, sector name and context) and with form description (See Figure 95). During the retrieval process of mental information, some parts of mental information can be externalized in early sketching. These early sketches are not sufficiently mature to be shared, interpreted, or used by other peoples; however, they are useful to develop their concepts or ideas.

Along with the cognitive processes, the previous literature review and our present experiments demonstrated that emotional reactions might control cognitive processes of designers in a way of generating stimuli and evaluating their results. For example, if an idea gets a positive feedback from designer, the cognitive operation of *selective attentio*n can be more easily activated to retrieve the necessary information from long-term memory. Designers then continue to elaborate the idea or move to others ideas. Regarding emotional reactions in an evaluative way, designers often evaluate the idea or sketches by their aesthetic harmony rules, and also evaluate them by hedonic quality (e.g. designer's satisfaction). Even though our verbalization protocol (EXP 1) was limited to quantify these emotional aspects of design in relation to their processing, the results from vocal expressions of designers led us to raise some empirical evidences (→§4.2.4.5). Moreover, during EXP 2, we identified the relationship between emotional aspects of design and their early sketches underlying our specific phase. We concluded that early sketches could sufficiently express their own semantic and emotional attributes. In particular, a 'good form' of sketches can elicit a positive feeling (valence) and a higher arousal state. Since early sketches are the first externalization of mental representations in the generative phase, their semantic and emotional responses may reflect the expected values of design solution. Hence, early representations (sketches) could play a role to convey design intents and predict semantic and emotional responses of consumers from the early stages of design.

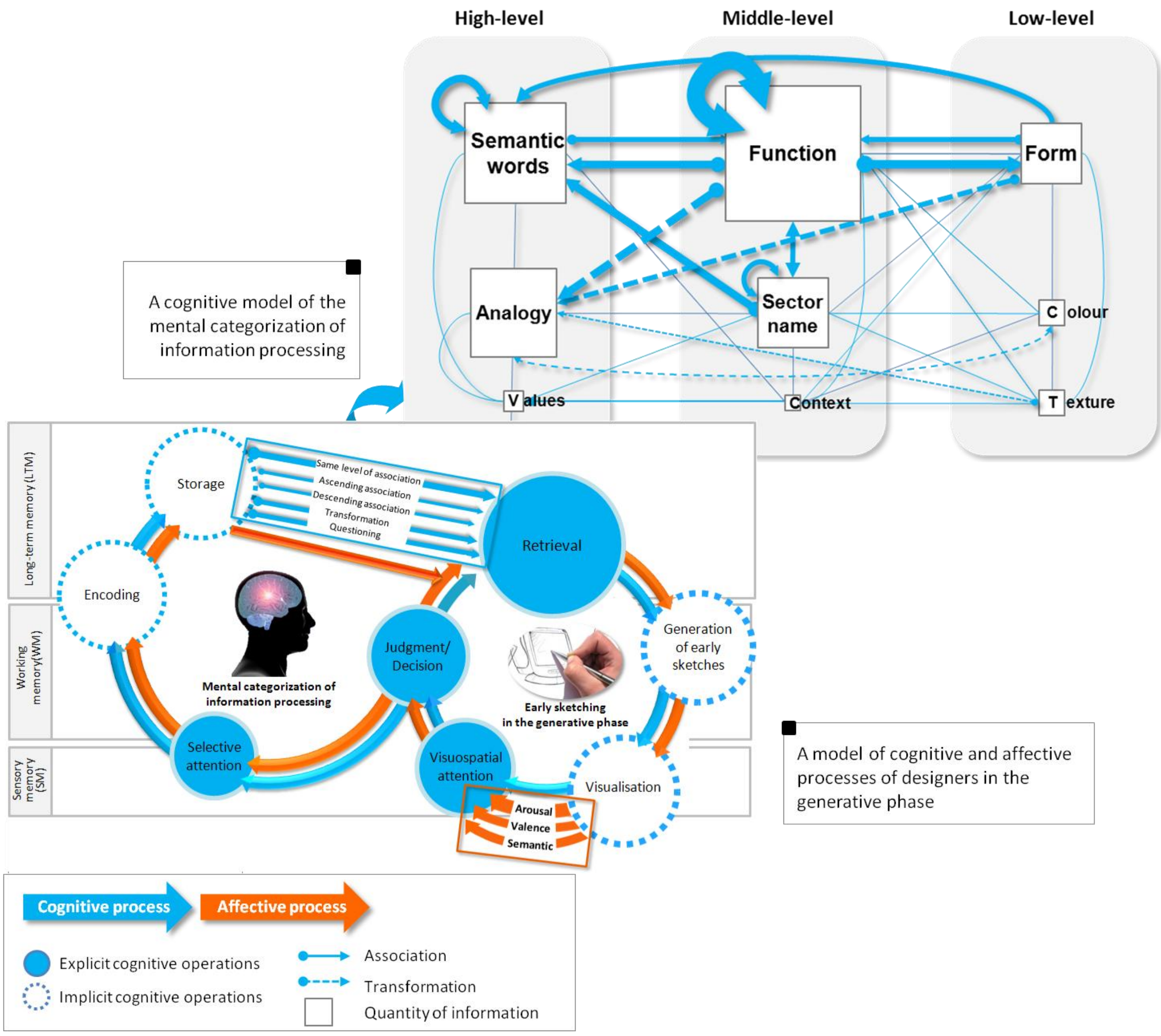


Figure 95. An integrated model of the cognitive and affective processes of designers in the generative phase

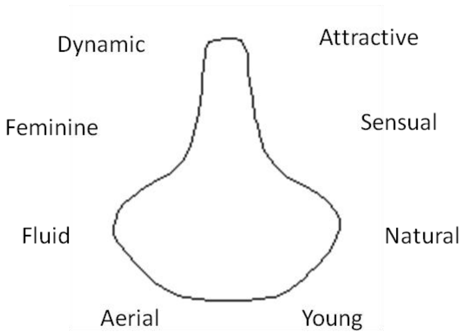
5.3 Specification for developing computational tools dedicated to the generative phase

Based on the three types of results (qualitative, quantitative and integrated), we derived a model depicting the mental categorization of design information processing in the generative phase. → §5.1 and §5.2. Particularly, this model allows us to explain actual design activities and to characterize what future computational tools shall be integrated. Moreover, given that the notion of information level was initially derived from the field of artificial intelligence, where it is used to develop specific computational algorithms, we developed a list of specifications for developing computational tools, specifically dedicated to the generative phase (See Table 15).

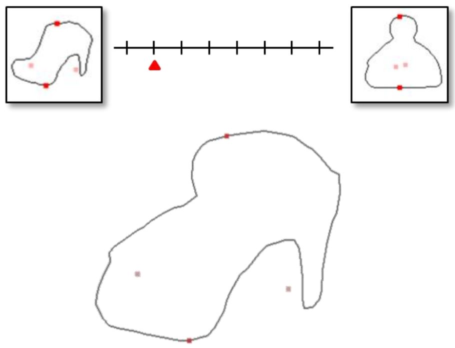
Table 15. Specification for computational tools dedicated to the generative phase

Category	*Detailed specification*
Structure of database	• Systems shall integrate twelve sectors of analogies and sub-sectors derived from 16 designers, including sport, biomorphism, shoes, luggage, etc. Given that those sectors were naturally raised and implemented by designers, the system should have a capacity to enlarge different sectors as designers do. • Systems shall provide a database of archetypes from different sectors as described above. • Systems shall provide gradual changes of morphing silhouettes between archetypes and those of different sectors. • Systems shall retrieve a novel form according to a high-level information and combination of different levels of design information as a query, for example, sportive, dynamic, fluid, classic, rounded and dynamic forms, etc.
Retrieval of design information	• Systems shall support association of design information in same level, ascending, or descending way, in conjunction with a predominant association, for examples, function ↔ function, function → form, sector name→ semantic words, etc. (see Figure 93). • Systems shall visualize a variation of archetypes according to high-level descriptors. • Systems shall show similar forms from one sector to another. • Systems shall provide all types of transformations and rearrangements of forms.
Evaluation Visualization Storage	• Systems shall assess aesthetic harmony rules or even suggest the rules. The objective evaluation will support a level of form adaptation according to semantic descriptors. • Systems shall put on record a trace of previous forms. It enables designers to continue varying the part of forms with previous ones on a new sheet. It is commonly used to designers with multiple sheets of sketches as well as layers. • Systems shall allow to record any phases of designer's work in order to consult them subsequently. • Systems shall facilitate the navigation of global or detail representations of a form. • Systems shall visualize a form from the thumbnail to 1:1 scale. Designers can determine their expecting proportion of form.
Designer's working environment	• Systems shall be compatible with other software used by designers, as part of the generation of sketches, such as Adobe illustrator, Photoshop, etc. • Systems shall support both individual and collaborative working environment of designers.

As an application, a list of specifications for developing computational tools dedicated to the generative phase has been applied and validated in the ''GENIUS'' project. This project aimed to develop the system supporting designer's activities in the early stages, including the information categorization process and the generation of new formal solutions. Current prototype is the first interactive software, which aims to demonstrate the feasibility of the database and to assess their functional specifications (See Figure 96). The next implementation of our specifications is still underway.



(a) Characterizing a form according to the semantic descriptions



(b) Morphing forms between archetypes from different sectors

(c) GENIUS Interface (prototype v.1)

(d) Support collaborative working environment

Figure 96. Examples of the GENIUS system

5.4 Summary of the contributions

The key contributions of the study in the perspectives of both scientific and industrial communities as follows:

- **A model of the cognitive and affective processes of designers, dedicated to mental categorization of information processing in the generative phase**

A scientific contribution of the thesis is a model of the cognitive and affective processes of designers, where they mentally categorize design information to generate early sketches. This model consists of two cycles that are the mental categorization of information and early sketching in the generative phase. First, a model of mental categorization of information processing focused specifically on the structure of design information (high, middle, and low-levels) and cognitive operations (association and transformation). It provides clues to identify how mental information is encoded and stored in long-term memory (LTM) and moved to working/short-term memory (WM/STM). This model was then extended to 'early sketching in the generative phase', because early sketches can be used as an external memory, and interact with internal memory of designers. In addition, along with the cognitive processes of designers, we illustrated how emotional reaction of designers may control this specific phase in generating stimuli and evaluating their results.

- **Specifications for computational tools dedicated to the generative phase**

In order to meet the industrial needs for developing computational tools to support the early stages of design, our model was translated into a list of system specifications. Specifically, this system specification can be used to develop computational tools dedicated to the generative phase. This involves the construction of databases (semantic descriptors, archetypes, divers analogy issues from different sector), and an association between design information, transformation of forms (morphing in terms of semantic descriptors, or analogy), also a support of the memorising process of design precedent, and so on. In the GENIUS project, which aims to support the generative phase performed by designers, specifications have being validated and integrated.

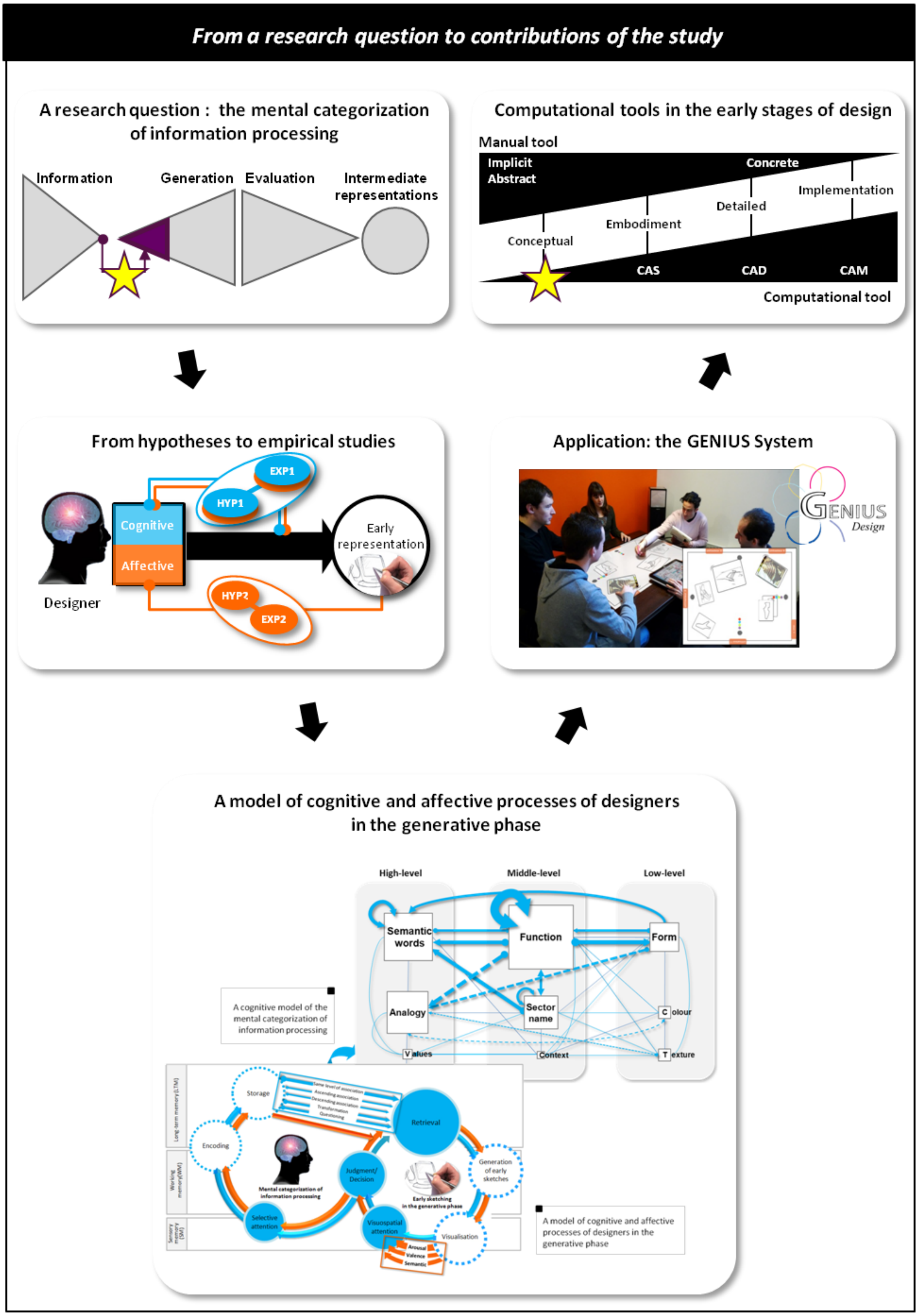


Figure 97. Summary of the contributions

VI. CONCLUSIONS AND PERSPECTIVES

6.1 Conclusions

This thesis focused on the 'mental categorization of information processing' in the generative phases, wherein designers employ various levels of mental information, and gradually integrate and synthesize them into their memory in order to further generate early sketches. In conjunction with cognitive aspects of design, we proposed that cognitive and affective processes, involved in this specific phase, should be modeled through understanding designer's mental process and its relationship with early representations (sketches) together.

By applying both an action research approach and laboratory-based experiments, we initially proposed a descriptive model of information processing involving memory theories drawn from cognitive psychology. To enrich and validate this model, we conducted two experiments with experts and novices designers in the product design domain. EXP 1 concerned cognitive and emotional aspects of design during mental categorization of information processing. EXP 2 focused on the relationship between emotional aspects of design and its representations underlying our specific phase of the study. Subsequent analysis finally yielded a model depicting the mental categorization of information processing performed by designers.

This model consisted of two cycles that are the mental categorization of information and early sketching in the generative phase. First, a model of mental categorization of information processing focused specifically on the structure of design information and cognitive operations. This model was then extended to 'early sketching in the generative phase' to explain constructive links between external and internal memory of designers via 'early representations'. In addition, along with the cognitive processes of designers, we illustrated how emotional reaction of the designers can control this specific phase in generating stimuli and evaluating the results. In doing a three-year project 'GENIUS', our model was translated into a list of specifications for developing computational tools dedicated to the generative phase, and implemented into the GENIUS system as an application of this study.

Original research advancements were pushed several areas: (1) this study explored an emerging topic of research, ''mental categorization of information processing in the generative phase''; (2) both cognitive and affective processes of designers have been jointly studied; (3) an action research approach and laboratory-based experiments led to the elicitation of the specific designer' activities; (4) the prediction of emotions from early representations (sketches) were also pioneered, finally (5) the integration theories and methods from psycho-physiology in design research enabled us to deepen our study.

6.2 Perspectives

Future research should address the following issues: cognitive, behavioral, and affective processes of designers, the prediction of emotions among inspirational sources, early representations, and final products, and development of computational support tools dedicated to early stages of design (See Figure 98).

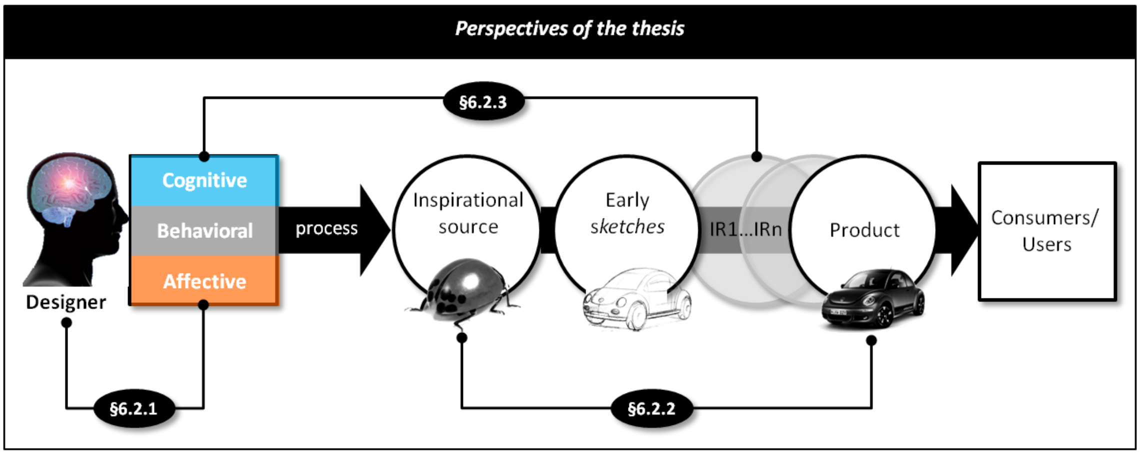


Figure 98. Three issues for future research

6.2.1 Cognitive, behavioral, and affective processes of designers

According to **Norman et al. (2004)** and references therein, there are three levels of processing: cognitive, behavioral, and affective. Each level is differently characterized according to its content, data flow, and modality, etc. All three levels are important for understanding both conscious and unconscious levels of information processing (See Figure 99). In this thesis, we focused particularly on the cognitive and affective processes of designers. For future research, we expect to combine and analyze other modalities for expressing cognitive and emotional aspects of design, especially at behavioral and affective levels.

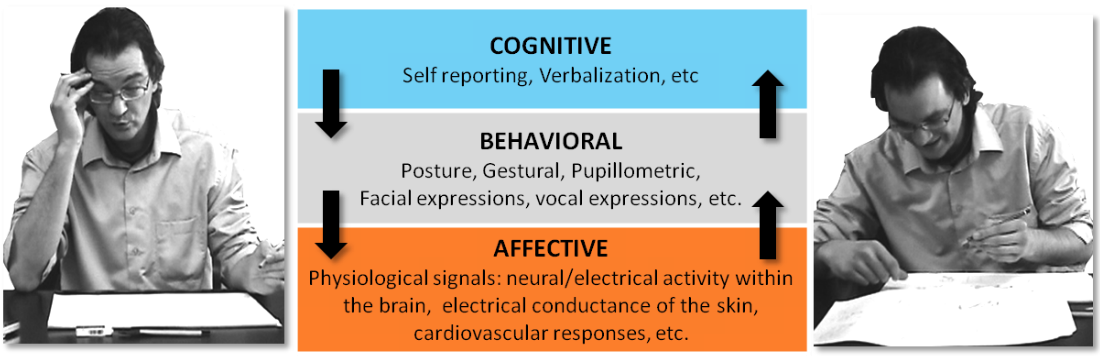


Figure 99. Three level of information processing (modified from Norman (2004))

Regarding the behavioral level, it involves hand movement, gesture, facial expression, posture of designers, etc. Some pioneers in behavioral studies have discovered that human body posture and movement can be an important affective communication channel **(Ekman & Friesen, 1967, Mehrabian & Friar, 1969, Bianchi-Berthouze & Kleinsmith, 2003)**. The complementary coding scheme for a posture and a gesture of designers can be of great interest for future research. In addition, concerning the affective level, we are planning to detect different physiological measures, including electrocardiogram (ECG), Electroencephalograms (EEGs), eye tracking, etc. in order to detect both emotional and cognitive state of designers. We can also benefit from an emerging research in Human Computer Interaction (HCI) community toward the development of wearable and mobile physiological sensors for the future work.

6.2.2 The prediction of emotions among inspirational sources, early representations, and product forms

In the early stages of design, designers employ a large variety of inspirational sources from different areas: comparable designs, beings, and phenomena from nature and everyday life **(Bouchard et al., 2008)**. Indeed this kind of analogy helps them to provide a high expressivity, a high-level of creativity, and a high emotional impact into the design solutions **(Wang, 1995; Bonnardel & Mamèche, 2005; Djajadiningrat et al, 2007)**. Therefore, for future research, we plan to expand a possible prediction of emotions over earlier phases of the design process, especially the informative phase. Thus, we are interested in the emotional link between inspirational sources and product forms, and the link between early representations (early sketches, 2D drawing, 3d mock-up, etc.) and final products. Finally, a link among inspirational sources, early representations, and product forms, may enable us to better understand how designers are putting emotions in their design solutions, and how these solutions are perceived by the consumers during the whole design process.

6.2.3 Computational tools dedicated to the early stages of design

From an industrial perspective, designers tend to develop the use of digital databases in design, and increasingly recognize the importance of computational tools within their activities. However, current commercial computational tools for designers are limited to the detailed design process, and the tools dedicated to the early stages of design have not yet come to the fore **(Restrepo, 2004; Büsher et al., 2004; Stapper & Sanders, 2005)**. It might be due to two weaknesses with existing tools: *utility of the functionalities* and *interface quality*. The former comes from a difficulty for understanding designers' cognitive activities in the early stages of design, which are relatively implicit and subjective **(Ullman et al., 1988)**. The latter originates from a lack of consideration for interactivity, particularly in the graphical interface **(Campos et al., 2007)**. Interface quality is very important considering the high-level of expectation held by designers, who are likely to be highly sensitive to the quality of the graphical interface.

In this thesis, as an application, we presented the GENIUS system, dedicated to the generative phase. Based on this system, further work must be done to develop computational tools, which can encompass the early stages of design and to enhance interface quality of the tools. Ultimately, these computational tools will further help designers to generate more expressive, creative, and pleasurable design solutions for the consumers.

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SYSNTHESIS OF THESIS IN FRENCH

INTRODUCTION GÉNÉRALE

Objectif de la recherche

Cette thèse a eu pour but de décrire comment les designers catégorisent mentalement l'information durant les étapes précoces de génération d'esquisses réalisées dans la phase générative. La finalité était de formaliser et développer un modèle de processus cognitif et affectif des designers, à travers la compréhension des processus mentaux et de leur relation avec les représentations précoces (esquisses).

Les objectifs donc étaient:

- de quantifier quel types d'informations mentales sont extraits et comment ces informations sont transformées et catégorisées à travers des opérations cognitives spécifiques durant les phases de génération d'esquisses;
- d'explorer les processus affectifs des designers qui entrent en jeu et interagissent avec les processus cognitifs lors des étapes de production de concepts et d'évaluation qui interviennent durant la phase générative;
- d'identifier la réponse émotionnelle vis-à-vis des premières représentations (les esquisses) ;
- de quantifier cette réponse émotionnelle en combinant les méthodes cognitives avec les approches physiologiques.
- de développer des spécifications pour le développement d'un outil computationnel dédié spécifiquement à cette phase.

Problématique de la recherche

Etant donné que les phases précoces de la conception sont aussi considérées comme parmi les plus intenses d'un point de vue cognitif, plusieurs recherches ont peu à peu investigué cette question afin de formaliser et de développer un modèle explicite de ces phases. Cependant, comme la plupart des recherches menées à ce jour portent plus sur les processus explicites relayés par une information externalisée, il y a un manque à combler entre la phase informative et les phases génératives précoces qui sont relativement implicites. Dans cette thèse, nous avons appelé cet espace encore indéfini le 'processus de catégorisation mentale de l'information'. Conjointement des aspects cognitifs du design, nous avons proposé de modéliser les processus affectifs présents dans cette phase, à partir d'une compréhension des processus mentaux des designers et de leur relation avec des représentations précoces telles que les esquisses. Dans cette thèse, nous avons établi la problématique suivante: **''comment modéliser les processus cognitifs et affectifs des designers en conception amont, et plus précisément durant le processus de catégorisation mentale de l'information réalisé lors de la phase générative?''**.

Apports de la thèse

Notre apport scientifique porte sur la formalisation d'un modèle des processus à la fois cognitif et affectif des designers. Ce modèle s'applique aux phases amont de la conception, lors desquelles les designers catégorisent mentalement l'information design afin de générer les premières esquisses. Ce modèle consiste en deux cycles que sont la catégorisation mentale de l'information et la génération précoce d'esquisses. D'autre part, afin de s'orienter plus vers des préoccupations industrielles pour développer des outils d'aide à la conception, ce modèle a permis de traduire des spécifications plus concrètes pour le développement d'un outil computationnel dédié spécifiquement à cette phase. Grâce à un travail mené dans le cadre du projet GENIUS, ces spécifications ont été intégrées et validées.

Originalité de la thèse

L'originalité des apports de recherche de cette thèse porte sur les points suivants: (1) cette recherche a exploré un champ émergent de la recherche, ''les processus de catégorisation mentale de l'information inhérents à la phase générative''; (2) les processus cognitifs et affectifs des designers ont été étudiés conjointement; (3) une approche de recherche-action a été combinée avec des expérimentations de laboratoire afin de formaliser les activités spécifiques des designers; (4) la prédiction des émotions à partir des représentations précoces telles que les esquisses reste aussi un champ inexploré en sciences de la conception, finalement (5) l'intégration de théories et méthodes issues de la psychologie et de la physiologie en sciences de la conception nous a permis d'approfondir les résultats de recherche.

Structure de document

Ce document de thèse se divise en six chapitres: Contexte, Etat de l'art, Problématique et Hypothèses, Expérimentations, Modélisation, Conclusion et Perspectives. Le chapitre I introduit le contexte industriel et académique. Dans le chapitre II, nous avons établi un état de l'art portant sur les aspects cognitifs et affectifs du design, et sur un récapitulatif des méthodes cognitives et physiologiques sur les thématiques du design et de la psycho-physiologie. Le chapitre III formule la problématique et les hypothèses de cette thèse. Dans le chapitre IV, deux expérimentations ont été proposées afin de tester les hypothèses de cette thèse. Le chapitre V porte sur les principaux apports de la thèse en mettant avant des perspectives scientifiques et industrielles. Le chapitre VI se poursuit par une conclusion générale qui récapitule les principaux points clés de la thèse. Il se conclue par une discussion à propos des orientations de recherches futures.

I. CONTEXTE

Ce chapitre introduit le thème majeur de notre recherche et décrit le contexte industriel et académique. La recherche en design est fortement liée à des enjeux théoriques et pratiques. La première section porte sur le secteur industriel avec en particulier des problématiques relatives aux domaines sociaux, économiques et technologiques. La deuxième section traite plus du contexte académique et explique en quoi la thématique de la cognition et des émotions est devenue un thème majeur en recherche interdisciplinaire

1.1 Contexte industriel

Les développements dans le domaine des sciences et des technologies qui datent de la révolution industrielle ont été d'un grand intérêt pour le monde scientifique; cependant, peu de recherches dans l'histoire se sont penchées sur le rôle des utilisateurs (consommateurs potentiels) et des designers. Depuis l'introduction massive de la notion de 'conception centrée utilisateur' durant les années 90, la recherche sur les utilisateurs dans le domaine des services pour améliorer les interfaces utilisateurs et améliorer l'utilisabilité, est devenue peu à peu quelque chose de commun. De nos jours, avec le passage d'une société de la connaissance à une société de la créativité, la recherche sur les activités cognitives des designers a amené des contributions très importantes pour la génération d'idées créatives. Ces contributions qui sont à la base des efforts réalisés afin de répondre aux besoins et désirs des designers, et ont amené des améliorations significatives **(Restrepo, 2004, Brown, 2008)**. En effet, l'expertise et les processus cognitifs et créatifs des designers pendant les phases précoces de la conception ont été reconnus comme un thème de recherche important. En même temps, les designers ont développé des bases de données numériques, qui ont pris une part de plus en plus importante dans leur activité grâce à la diffusion massive des technologies de l'information (NTIC) **(Pasman, 2003; Büsher et al., 2004; Restrepo, 2004; Jung et al., 2007; Bouchard et al., 2008)**. Cependant, le développement d'outils computationnels pour les designers s'est limité aux technologies du prototypage rapide, tels que la Conception Assistée par Ordinateur (CAO), la Fabrication Assistée par Ordinateur (FAO), ou le Style Assisté par Ordinateur (SAO) (voir Figure 1). Cela est dû au fait que les activités des designers sont relativement implicites et mettent en jeu des représentations mentales très riches pendant les phases précoces de la conception **(Ullman, Dietterich, & Stauffer, 1988)**, mais difficiles à appréhender.

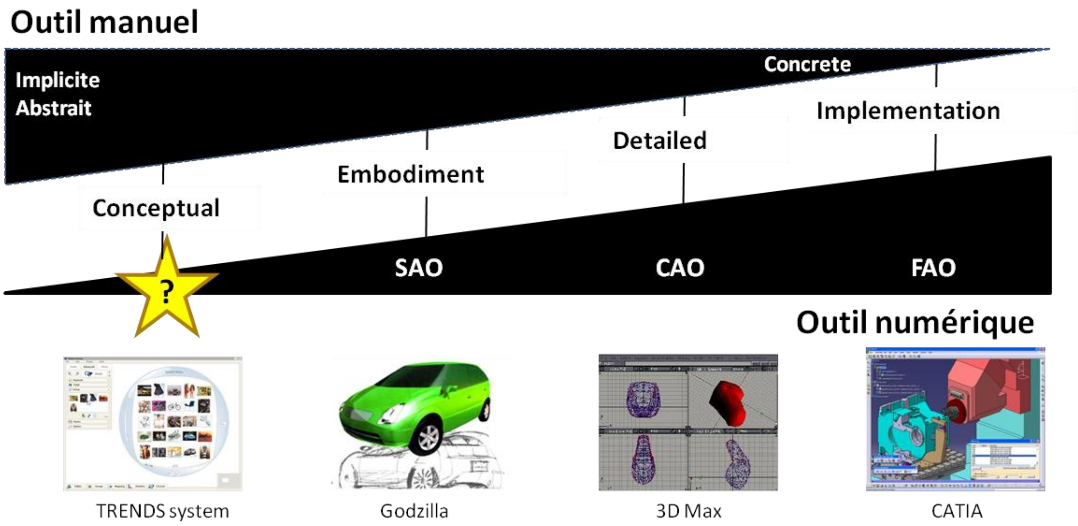


Figure 100. Evolution d'outils numériques d'aide à la conception (Kim et al., 2009a)

1.2 Contexte académique

Etant donné que les phases les plus amont de la conception sont considérées comme parmi les plus intenses du point de vue cognitif, de plus en plus de recherches tendent progressivement à investiguer, formaliser et développer un modèle explicite des phases amont **(Simon, 1969; Schön, 1983; Gero, 2006; Bilda, 2006; Goldschmidt, 1994; Bouchard et al., 2003, 2008; Coley et al., 2007)**. En accord avec l'intérêt croissant pour les recherches portant sur les activités cognitives des designers, les recherches sur la cognition et les émotions ont été considérablement développées depuis les vingt dernières années dans le domaine des sciences cognitives. Jusqu'à présent la plupart de ces recherches ont porté sur les processus cognitifs dits *froids* – qui s'étendent de la prise de décision jusqu'à la mémorisation des informations, et des avancées de recherche importantes ont émergé à propos de l'interrelation qui existe entre la cognition et les émotions **(Phelps, 2006; Ochsner & Gross, 2007)**. En étendant ce mouvement au domaine des sciences de la conception, **Norman (2004)** et **Desmet & Hekkert (2007, 2009)** ont continué à formaliser les processus émotionnels en explorant la relation qui existe entre les aspects émotionnels et le design. La Figure 2 illustre le fait que cet intérêt est finalement devenu un thème majeur de la recherche interdisciplinaire non seulement en sciences de la conception, mais aussi dans ceux de la psychologie, de l'informatique, etc.

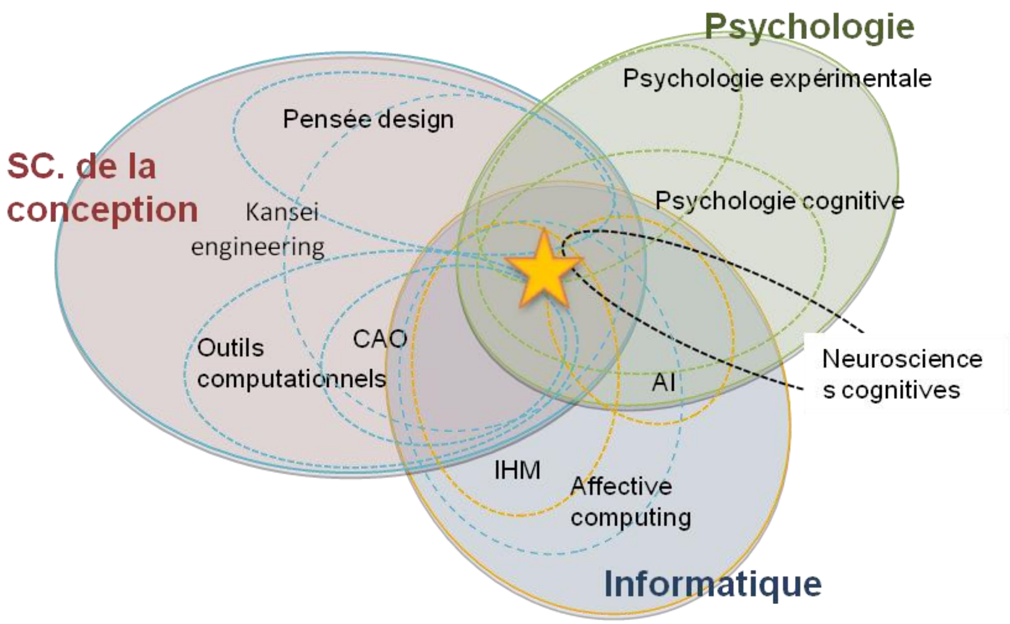


Figure 2. Positionnement scientifique en recherche interdisciplinaire

Dans ce contexte, notre recherche a eu pour objectif de développer de nouveaux modèles et outils qui puissent être utilisés dans les phases amont de la conception, en numérisant partiellement ces phases amont selon trois étapes successives: (1) identifier les connaissances, règles et compétences qui étayent les processus cognitifs des concepteurs **(Rasmussen, 1983)**; (2) traduire les règles design en algorithmes; et (3) développer des outils computationnels qui puissent être utilisés par les designers eux-mêmes ainsi que les autres professionnels impliqués dans les phases collaboratives amont de la conception **(Bouchard et al., 2008)**. Plus précisément, cette thèse porte sur les toutes premières étapes de recherche de concepts, en proposant une modélisation les processus cognitifs et affectifs des designers qui interviennent tout particulièrement lors des phases de catégorisation mentale de l'information durant les phases génératives de production d'esquisses.

1.3 Conclusion

Dans une société de la créativité, les designers peuvent être considérés comme apportant une contribution très importante à la génération d'idées créatives et plus généralement à l'ensemble des efforts réalisés pour s'adapter aux besoins et désirs des consommateurs. Leur activité apporte une valeur ajoutée importante dans de nombreux domaines de la création industrielle **(Resnick, 2007; Brown 2009)**. Cette nouvelle forme d'innovation a été dénommée *innovation par le design*. D'un point de vue à la fois microscopique ou macroscopique, de nombreuses statistiques ont démontré comment l'analyse et la formalisation des processus cognitifs et créatifs des designers lors des phases amont de la conception peuvent amener à innover et à accroître la compétitivité d'une entreprise et de la nation **(Cox, 2005; BCG, 2009; EU report, 2009)**.

Nous pouvons ainsi noter un intérêt croissant pour les aspects cognitifs et affectifs relatifs au designer pendant les phases précoces de la conception. La diffusion des technologies de l'information (IT) a conduit les designers à développer des bases de données numériques qui intègrent des données design. Celles-ci offrent un accès accru à une information variée de solutions attendues par le consommateur et permettent de réduire les délais de conception (**Pasman & Stapper, 2003; Büsher et al., 2004; Keller, 2005; Jung et al., 2007; Bouchard et al., 2008; Prats et al., 2009)**. Cependant la majorité des technologies est plutôt dédiée aux phases de conception détaillée, bien que les phases amont de la conception correspondent à des processus cognitifs très riches en information, qui seraient susceptibles d'améliorer considérablement le processus de conception s'ils étaient supportés par des outils d'aide à la conception.

Dans ce contexte il est nécessaire de mieux comprendre les activités des designers lors des phases précoces de la conception. Etant donné que les activités des designers sont relativement implicites et subjectives et mettent en œuvre des représentations mentales riches lors des phases amont de la conception **(Ullman et al., 1990)**, leur formalisation pourrait être investiguée et conduire à une compréhension plus fine des processus cognitifs des designers. Finalement, il serait alors possible de développer des outils computationnels dédiés aux phases amont de la conception pour s'orienter vers une numérisation et une optimisation du processus de conception global. Pour ce faire il nous a semblé pertinent de mettre en application une recherche de type recherche-action et des expérimentations de laboratoire. Ces approches nous ont permis non seulement de construire un modèle des processus cognitifs, mais aussi de s'appuyer sur une approche à la fois théorique et de type expérimental afin d'analyser les activités cognitives des designers.

II. ETAT DE L'ART

Nous pouvons constater un intérêt croissant témoigné par un grand nombre de recherches qui sont actuellement menées sur l'activité cognitive des designers, et plus récemment sur le lien qui existe entre les aspects cognitifs et affectifs de l'activité de design. Nous proposons une analyse critique de ces travaux et discutons la manière de mesurer ou de capturer les aspects implicites de l'activité de design. Finalement, le chapitre II conclue par une synthèse des apports issus de la littérature et par une première expression de notre problématique de recherche, qui a conduit à la formulation de la problématique et au développement des hypothèses dans le chapitre III.

Introduction

Selon **Cross (2007, 2008)**, la connaissance en design réfère à trois types de sources: les personnes, les processus et le produit. Dans notre contexte, ces sources peuvent être interprétées par les designers et les consommateurs (personnes), les processus génératifs amont (processus) et les représentations précoces du produit (produits). Notre état de l'art a porté sur ces trois types de sources et a permis de les structurer selon le schéma présenté (voir Figure 3).

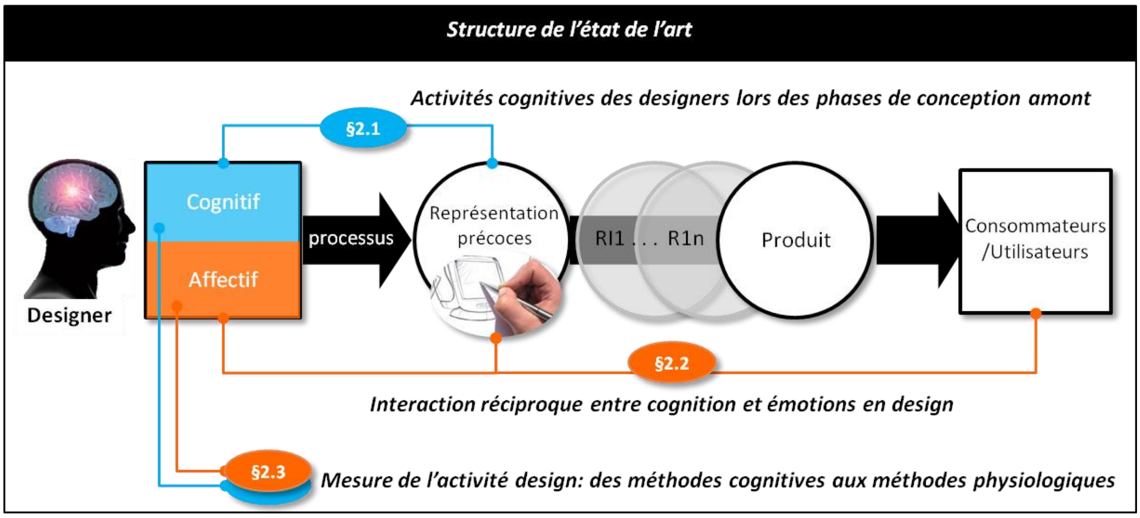


Figure 3. Structure de l'état de l'art

2.1 Activités cognitives des designers lors des phases de conception amont

2.1.1 Formalisation des processus cognitifs et informationnels mis en œuvre par les designers durant les phases amont de la conception

Les phases amont de la conception couvrent les processus informationnels et de génération d'idées (aussi appelées "conceptualisation") **(Bouchard, Lim, & Aoussat, 2003; Restrepo, 2004)**. Durant les phases précoces de la conception, les designers assimilent une grande quantité d'informations dont les niveaux d'abstraction sont variés. Ils réduisent peu à peu l'abstraction en rajoutant de plus en plus de contraintes **(Bouchard et al., 2003)**. **Bouchard et al. (2003)** ont modélisé les processus cognitifs des designers durant les phases amont de la conception en rendant explicites les processus informationnels qui entrent en jeu. Selon ce point de vue, les designers engagent un cycle informationnel qui inclue les phases informative, générative et décisionnelles (évaluation - sélection) afin de produire des représentations intermédiaires (IRs) développées de manière évolutive. **Goldschmidt (1994)** a effectué des recherches sur les images mentales ou physiques mises en œuvre durant la totalité du processus de conception. Les représentations intermédiaires peuvent être implicites ou explicites, et apparaître sous forme de cahier des charges design, de planches de tendances, d'esquisses 2D/3D, de modèles de style, de modèles géométriques numériques, de maquettes, de prototypes, etc. Les représentations intermédiaires sont utilisées de manière stratégique en fonction du contexte design, des phases dans lesquelles on se situe, des objectifs design, ou du contexte culturel. Etant donné que les phases amont de la conception sont considérées comme figurant parmi les plus intenses du processus de conception d'un point de vue cognitif **(Nakakoji, 2005)**, plusieurs études basées sur le design ou l'architecture ont porté sur le processus de génération d'esquisses des designers, et en particulier ceux qui ont lieu durant les phases génératives **(Schön & Wiggins, 1992; Goldschmidt, 1994; Suwa & Tversky, 1997; Bilda & Gero, 2007; Coley et al., 2007)**. Depuis le début des années 1990, plusieurs recherches dédiées à l'activité de génération d'esquisses des designers ont émergé dans le domaine de l'ingénierie de la conception (**Ullman et al., 1990; Goel, 1995; Purcell & Gero, 1998 ; Boujut & Blanco, 2003; Yang, 2009)**. A ce jour, peu d'études ont investigué des questions relatives aux sources d'inspiration utilisées par les designers dans la phase d'information **(Eckert & Stracey, 2000; Keller, 2005; Bouchard et al., 2008)**. De plus, le lien entre la phase d'information et les phases précoces de génération a été relativement négligée, et les expériences spécifiques des designers produits n'ont pas encore réellement été investiguées.

2.1.2 Définition de 'processus de catégorisation mentale de l'information'

Le lien entre la phase dite d'information et les phases précoces de génération incluent la génération de nouvelles idées et de nouvelles solutions. La phase générative démarre sur la base de nombreuses images mentales, des objectifs mémorisés à partir du cahier des charges, et d'autres informations issues de projets antérieurs **(Bouchard et al., 2003)**. Ce processus a été reconnu comme une expérience individuelle des designers qui se manifeste par des opérations cognitives répétitives **(Jin & Chuslip, 2006)**. Pendant les phases génératives précoces, certaines parties des images mentales peuvent être externalisées à travers les esquisses. Ces esquisses précoces ne sont pas suffisamment matures ou adéquates pour être partagées ou interprétées par d'autres acteurs. En revanche, elles sont utilisées comme des représentations externes (i.e., mémoire externalisée qui agit comme un système de signes durant l'inspection en cours) **(Goldschmidt, 1994; Suwa & Tversky, 1997; Crilly et al., 2008; Prats et al., 2009)**. Les représentations externes (e.g., les premières esquisses) permettent d'instaurer une conversation réflexive entre le designer et le produit **(Suwa & Tversky, 1997; Crilly et al., 2008)**. Des recherches antérieures ont montré que les représentations externes permettent aux designers d'identifier des erreurs qui sont ensuite utilisées comme bases pour la génération de nouvelles idées **(Akin, 1978)**. De la même manière **Crilly et al. (2008)** ont noté que les designers sont engagés dans des *conversations bi-directionnelles* avec ce type de représentations en formulant et reformulant leurs intentions durant les activités de représentation (voir aussi Schön's "Seeing–Drawing–Seeing model" **(Schön & Wiggins, 1992)**. L'information interne et externe interagit avec les acteurs de manière évolutive et intégrée et est synthétisée en catégories qui contribuent à s'orienter vers les solutions design via le processus mental des designers (**Bouchard et al., 2003)**.

Nous avons travaillé sur la formalisation des processus cognitifs lors desquels l'information design est catégorisée juste avant l'activité de génération d'esquisses qui ponctue le début des phases génératives (voir Figure 4).

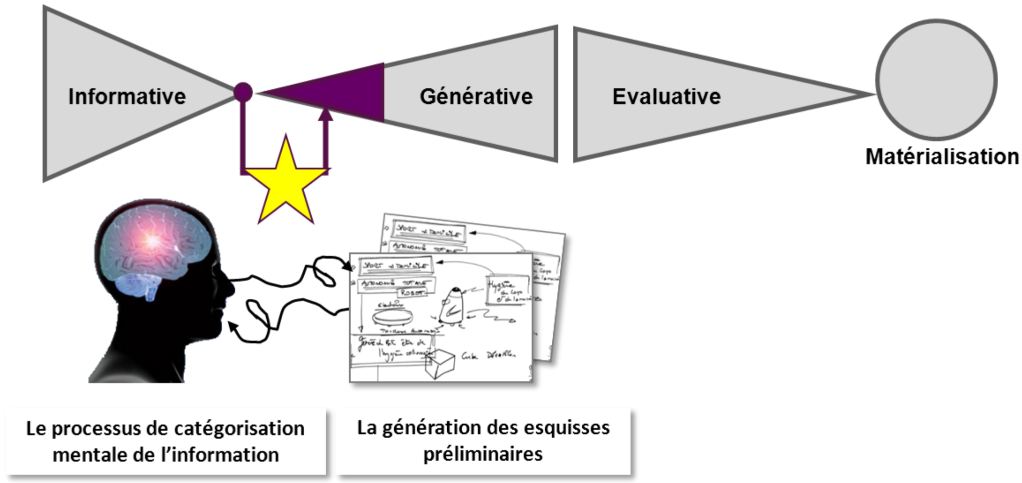


Figure 4. Catégorisation mentale de l'information pendant les phases génératives

Plus précisément, notre objectif a été d'identifier le type d'opérations cognitives qui permettent d'extraire l'information de notre mémoire et de définir comment cette information est transformée ou catégorisée pendant la réalisation des premières esquisses. Nous proposons une définition de trois expressions qui seront souvent utilisés dans cette thèse : le processus de catégorisation mentale de l'information, la phase générative, et la génération des esquisses préliminaires

- **Le processus de catégorisation mentale de l'information** est le processus selon lequel les designers emploient différents niveaux d'information mentale qu'ils intègrent, structurent, et synthétisent peu à peu dans leur mémoire afin de générer ensuite les premières esquisses.
- **La phase générative** est caractérisée par la génération d'esquisses jusqu'à l'aboutissement à la "bonne forme" d'un ou plusieurs concept(s). Certaines parties des images mentales sont externalisées à travers les esquisses dans cette phase.
- **La génération des esquisses préliminaires** correspond à la production des premières représentations externalisées des représentations mentales. Ces esquisses ne sont pas

suffisamment matures ou adéquates pour être partagées ou interprétées par d'autres acteurs. En revanche, elles sont utilisées comme des représentations externes pour le designer qui les produit.

2.1.3 Modèle de processus informationnel relatif aux théories liée à la mémoire

Afin de formaliser le processus cognitifs des designers, nous utilisons en référence trois modèles théoriques issus de la psychologie cognitive et adaptés à nos objectifs de formalisation: le modèle **d'Broadbent (1958)**, celui d'**Atkinson & Shiffrin (1968)** et celui de **Baddeley (2009)** qui fait intervenir la mémoire de travail (Annex B). Afin de considérer de manière globale l'activité amont de conceptualisation, et en nous basant sur les premières analyses des informations recueillies, nous avons finalement retenu les 6 opérations cognitives suivantes: l'attention sélective, l'attention visuo-spatiale, le questionnement, l'association (ascendante, descendante ou équi-niveau), la transformation et le jugement orienté vers la décision. Les trois opérations cognitives de questionnement, d'association et de transformation sont mises en œuvre lors du processus de rappel entre la mémoire court-terme et la mémoire long-terme. Elles sont aussi répertoriées dans le modèle de Geneplore développé par **Finke et al. (1992).** Ces auteurs ont décrit plusieurs types d'opérations cognitives sollicitées lors des phases génératives. Ces opérations sont les suivantes: rappel d'information en mémoire, association, synthèse mentale, transformation mentale, transfert analogique et réduction catégorielle. Certaines d'entre elles, telles que la synthèse mentale ou la réduction catégorielle sont difficiles à identifier au travers de verbalisations ou d'esquisses, mais les trois restantes (rappel d'information en mémoire, association et transformation) peuvent être appréhendées dans la plupart des cas **(Finke et al., 1992)**. D'autre part nous avons observé que les designers peuvent se poser des questions lors du processus de rappel. C'est pourquoi nous avons rajouté l'opération de questionnement. Les autres opérations que nous avons intégrées dans notre modèle théorique sont celles d'attention sélective, d'attention visuo-spatiale, de jugement et de décision d'après le modèle défini par **Harris (1992), Ball & O'Callaghan (2001)** et **Style (2005)**.

Le schéma de codage que nous avons défini nous a amenés à une compréhension relativement exhaustive du lien qui peut exister entre les représentations mentales lors du processus de rappel et l'information externe lors des activités de génération d'esquisses, ainsi que les flux liés au processus cognitif de catégorisation mentale de l'information. La définition des termes utilisés est présentée dans le Tableau 2 et l'Annexe A.

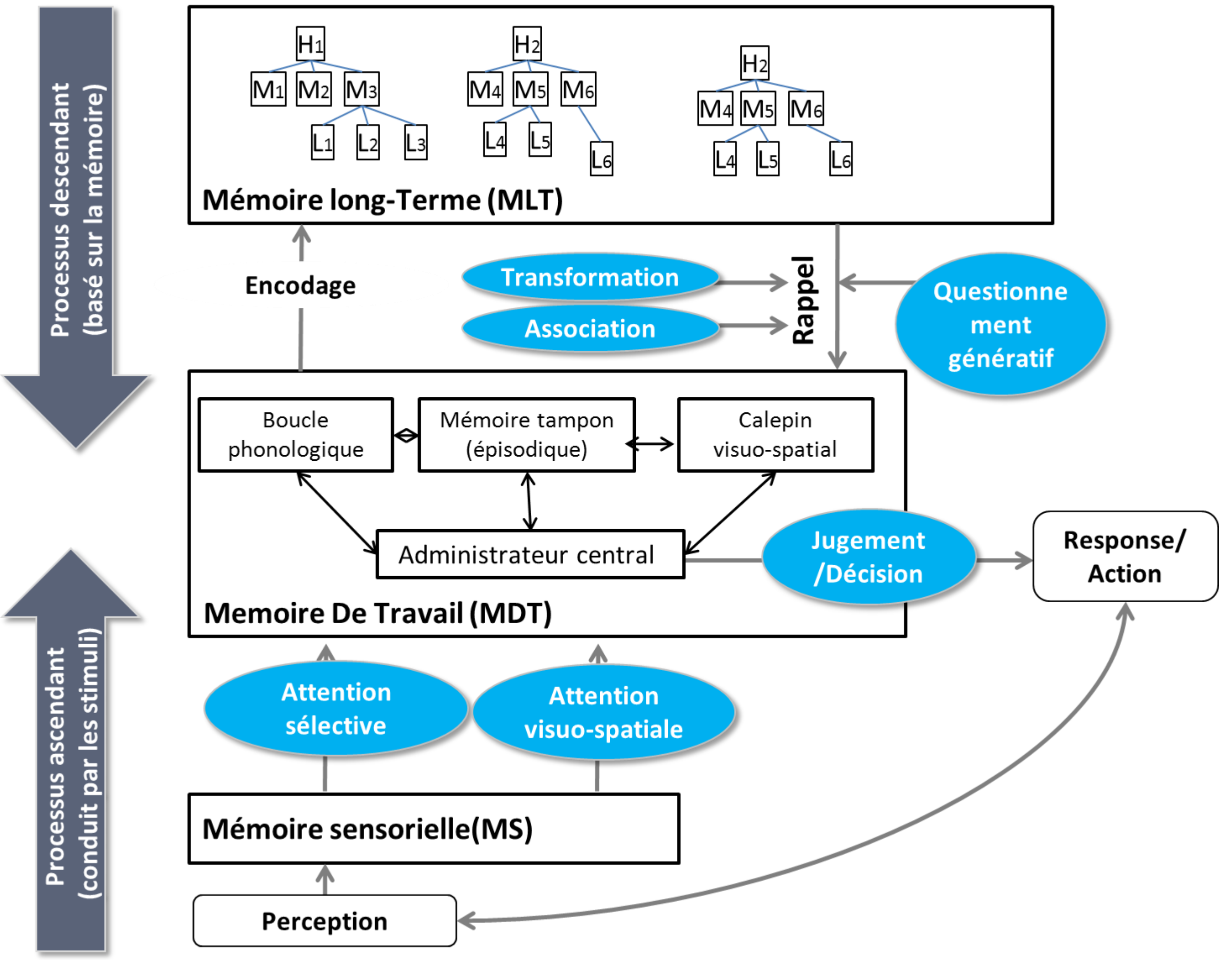


Figure 5. **Modèle de traitement de l'information (selon les modèles d'Broadbent (1958), d'Atkinson & Shiffrin (1968), et d'Baddeley (2009))**

2.1.4 Synthèse: nécessité de formaliser un modèle explicite du processus de catégorisation mentale de l'information'

Dans la section 2.1, nous avons défini les processus cognitifs des designers en particulier lors des phases amont de la conception. Etant donné que les phases amont de la conception sont considérées comme parmi les plus intenses du processus de conception d'un point de vue cognitif, et aussi celles qui apportent le plus de nouveauté lors de la génération de nouvelles idées, plusieurs recherches ont peu à peu investigué ce sujet afin de formaliser et développer un modèle explicite des phases amont; cependant, les phases les plus amont du processus de la conception restent encore peu formalisées ou comprises.

Cela est dû au fait que la plupart de la recherche en design dépend des avancées provenant d'études empiriques **(Coley et al., 2007)**; les résultats de ces recherches ont souvent négligé les aspects cognitifs qui incluent la construction, la catégorisation et la mise en application de l'information design pour la génération d'idées lors des phases amont de la conception, qui restent relativement implicite. Dans cette thèse, nous avons défini cette phase en tant que 'processus de catégorisation mentale de l'information', lors duquel les designers catégorisent mentalement l'information design afin de générer les esquisses préliminaires. Cette phase correspond au lien qui peut exister entre la phase d'information et les phases génératives précoces.

La question posée est alors la suivante : comment établir un modèle explicite de 'processus de catégorisation mentale de l'information'? Comme **Finger & Dixon (1989)** et **Takeda et al. (1990)** l'indiquent, un modèle descriptif peut aider à clarifier et définir ce qu'est le design d'un point de vue théorique. Ainsi, nous avons développé un modèle descriptif du processus informationnel basé sur les théories de la mémoire considérés à partir du point de vue de la psychologie cognitive dans la section 2.1.3. Ce modèle descriptif sera affiné et enrichi via une analyse expérimentale.

2.2 Interaction réciproque entre cognition et émotions en design

2.2.1 Aspects émotionnels du design durant les processus cognitifs

Sur la base d'un état de l'art sur les recherches théoriques et expérimentales issues des sciences de la psychologie et des neurosciences, nous proposons une relation bi-directionnelle qui semble importante pour comprendre l'impact émotionnel sur les processus cognitifs des designers lors des phases génératives ou d'évaluation. ''L'impact émotionnel relatif à la génération'' joue un rôle important afin de réguler le processus mental de traitement de l'information, en activant l'information nécessaire et en modifiant l'attention afin de répondre à la demande de la tâche en cours **(e.g. Isen, 1999; Ochsner & Gross, 2005; Barrett et al., 2007)**. L'information design consiste en différents niveaux d'abstraction: haut niveau (valeur, descripteur sémantique, analogie, style), moyen niveau (nom de secteur, contexte, fonction) et bas-niveau (couleur, forme, texture) **(Bouchard et al., 2009)**. Les designers activent l'information nécessaire en croissant ces différents niveaux d'attributs. Cette tâche met en œuvre un impact émotionnel important vis à vis du processus cognitif. Par exemple, lors de la description d'un "chariot élévateur", des adjectives sémantiques tels qu'efficace, robuste, rapide, etc. peuvent être cités **(Schütte & Eklund, 2001)**. Par opposition, ''L'impact émotionnel relatif à l'évaluation'' est mis en œuvre lorsque les designers activent leurs propres émotions lorsqu'elle s'auto évaluent ou jugent leurs idées ou celles de leur collèges **(e.g. Bouchard et al., 2008,2009; Clore & Huntsinger, 2007,2009)**. Parfois ils effectuent un jugement ou une évaluation d'une information de type bas-niveau par une information de type haut-niveau. Par exemple. Ils peuvent aussi réaliser un jugement ou une évaluation selon des valeurs hédoniques. Ces deux voies (générative/évaluative) sont en relation étroite et s'influencent mutuellement durant le processus cognitif lors des phases amont de la conception.

Tableau 1. Impact émotionnel lors des processus cognitifs en phase générative (Kim et al., 2010c)

relatif à la génération		
(G1) Dimension esthétique à travers des règles d'harmonie	Activation de l'information nécessaire en croissant ces différents niveaux d'attributs (descriptions sémantiques, noms de secteurs, formes, etc.)	Bouchard et al., 2009
(G2) Fraîcheur de l'information design	Régulation de l'attention afin de l'adapter à la tâche en cours par un 'feedback affectif'	Isen, 1999; Ochsner & Gross, 2005; Barrett et al., 2007; Clore & Huntsinger, 2007;
relatif à l'évaluation		
(E1) Cohérence intrinsèque des solutions	Evaluation des concepts par les règles d'harmonie mises en œuvre	Bouchard et al., 2008,2009 ; Clore & Huntsinger, 2007,2009
(E2) Jugement/évaluation selon des valeurs hédoniques	Evaluation hédonique de concepts, soit vis à vis de la satisfaction du designer	Isen, 1999; Russell et al., 2003; Cabanac & Bonniot-Cabanac, 2007

2.2.2 Aspects émotionnels relatifs aux représentations précoces de la conception

Les designers font intentionnellement appel à la dimension émotionnelle, et ce durant l'ensemble du processus de conception. Ils cherchent à provoquer à travers leurs propositions de solutions design des réponses physiologiques et comportementales spécifiques auprès des consommateurs **(Crilly et al., 2008)** (voir Figure 6)**.** Particulièrement, pendant les phases les plus amont de la conception, ils essaient de répondre au cahier des charges en s'orientant vers la recherche de la bonne forme. Ils intègrent cette intention dès les premières représentations sous forme d'esquisses lors de la recherche de la bonne forme. La forme du produit joue ainsi un rôle majeur comme précurseur des réponses cognitives et émotionnelles des consommateurs d'un produit **(Bloch, 1995; Kang & Yamanaka, 2009; Acuna & Sosa, 2010)**.

Figure 6. Intention design et réponse consommateur vis à vis du produit (Crilly et al. 2008)

En réalité, le consommateur est seulement en contact avec le produit final, qui fait intervenir simultanément différent attributs produit, incluant la forme, la couleur, la texture, le nom de la marque, le contexte etc. Ainsi, il est difficile de savoir si la forme du produit véhiculée selon l'intention des designers permet réellement d'anticiper la réponse des consommateurs.

L'intérêt croissant dans le domaine de la conception assistée par ordinateur accélère la formalisation du lien entre la forme du produit et la sémantique ou les émotions associées **(Hsiao & Wang, 1999; Hsiao & Liu, 2002; Chuang & Chen, 2009; Lesot et al., 2010).** Cependant, ces recherches sont encore limitées aux représentations concrètes, qui incluent les modèles numériques 2D et les prototypes numériques 3D. Ces modèles ne sont pas suffisamment représentatifs des phases précoces avec des représentations incomplètement définies telles que des esquisses et des termes sémantiques ou émotionnels générés par les designers lors des phases amont de la conception. De plus, plusieurs études ont porté sur l'évaluation d'esquisses préliminaires en termes de créativité **(Bonnardel & Marmèche, 2005)**; cependant, il n'y a pas encore eu de recherche à notre connaissance qui ont investigué la relation entre les esquisses préliminaires et la réponse émotionnelle.

2.2.3 Synthèse: considération insuffisante de l'impact émotionnel durant les processus cognitifs relatifs à l'élaboration des représentations précoces

Dans la section 2.2, nous avons décrit les aspects affectifs des designers relatifs aux processus cognitifs qui ont lieu lors des phases génératives amont, et l'impact émotionnel mesuré à travers les représentations précoces inhérentes à cette phase (esquisses). Notre état de l'art a été orienté principalement vers deux directions présentées ci-dessous.

- **Prise en compte insuffisante des processus affectifs des designers conjointement des processus cognitifs**

L'interaction entre des processus cognitifs et affectifs constitue un sujet émergent. Les résultats de recherche sur ce thème sont encore rares dans la communauté scientifique. Les contributions majeures de la section 2.2.2 présentent une analyse *bi-directionnelle* de l'impact émotionnel sur les processus cognitifs des designers en générant les stimuli et aussi en évaluant les résultats, selon la boucle ''seeing-drawing-seeing'' évoquée par **Schön & Wiggins (1992)**. Cette analyse doit permettre de formaliser l'impact émotionnel en relation étroite avec les processus cognitifs inhérents aux phases amont de la conception, lors de la génération d'esquisses. Il est nécessaire de mener des études complémentaires afin de consolider les modèles théoriques et d'apporter des supports lors de la génération d'esquisses. L'analyse des processus affectifs des designers peut s'appuyer en partie sur la dimension émotionnelle provoquée par des représentations précoces.

- **Considération insuffisante des aspects émotionnels en réponse aux représentations précoces :**

Les designers débutent avec des représentations mentales lors des phases amont de la conception; leurs esquisses préliminaires sont les premières représentations externalisées de leurs représentations mentales. Une formalisation de la réponse émotionnelle relative aux esquisses préliminaires présente ainsi un grand intérêt vis-à-vis de nos objectifs de recherche. Nous émettons l'hypothèse selon laquelle les esquisses préliminaires peuvent véhiculer des valeurs émotionnelles fortes, qui sont amenées de manière intentionnelle de la part des designers. Jusqu'à présent, cependant, nous n'avons pas mentionné d'analyses émotionnelles qui étudient les réactions émotionnelles provoquées par des esquisses. Nous avons souhaité investiguer ce point dans notre thèse.

2.3 Mesure de l'activité design: des méthodes cognitives aux méthodes physiologiques

2.3.1 De nombreuses modalités pour exprimer les dimensions cognitives et émotionnelles des designers

Etant donné que l'analyse de l'activité cognitive des designers constitue un intérêt à la fois important et pluridisciplinaire dans le monde scientifique, de nombreuses méthodes et techniques, qui incluent la psychologie, l'Ingénierie Kansei, et les neurosciences, ont été utilisées et appliquées en sciences de la conception. La Figure 7 illustre les principales méthodes utilisées dans différentes disciplines selon les trois axes: (1) l'axe X représente un éventail de modalités allant d'expressions linguistiques à des expressions non linguistiques; (2) l'axe droit Y représente l'effort nécessaire pour la manipulation d'instruments pendant l'expérience (Léger-Lourd); et (3) l'axe gauche Y représente les domaines d'application dans lesquels ces méthodes peuvent être employées

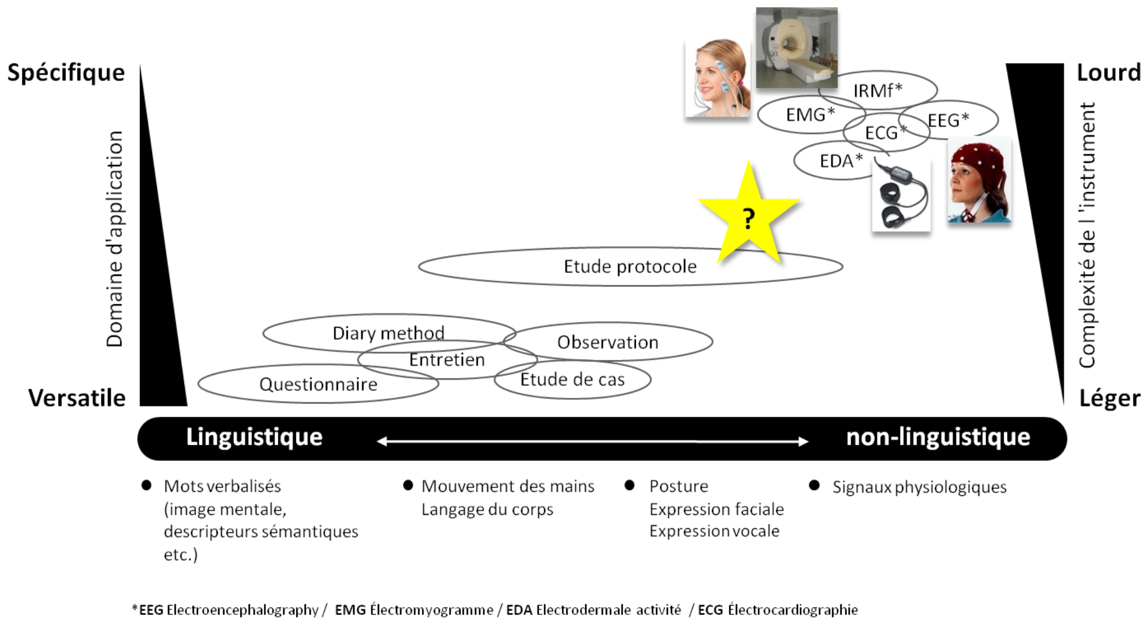


Figure 7. Principales méthodes pouvant être appliquées pour mesurer les émotions relatives à l'activité des designers (non exhaustive)

Les modalités mises en œuvre par les designers varient selon les niveaux linguistique (mots verbalisés: images mentales, descripteurs sémantiques, etc.), caractéristiques vocales, expressions faciales, comportement corporel (mouvements de la main, gestes, posture), et signaux physiologiques.

Dans le domaine de la recherche en sciences de la conception, plusieurs analyses ont été réalisées sur les aspects cognitifs des designers en utilisant des méthodes d'observation et des protocoles de verbalisation **(Akin, 1978; Cross et al., 1996; Suwa & Tversky, 1997; Eastman, 2001; Bilda & Gero, 2007; Coley et al., 2006)**. En définissant des schémas de codage spécifiques relatifs à l'analyse protocolaire tels que les verbalisations, le mouvement des mains, ou les caractéristiques relatives au dessin, les opérations cognitives et les informations traitées ont été analysées et quantifiées. Les schémas de codage les plus utilisés sont ceux de **Gero & McNeill (1988), et Suwa et al., (1998)**.

Cependant, étant donné que les aspects émotionnels des designers sont difficiles à exprimer et traduire sous forme lexicale, il est nécessaire d'investiguer des modalités plus subtiles des designers. Des études comportementales ont été réalisées précédemment sur la posture corporelle et les expressions faciales, ces deux canaux constituant des canaux important de l'expression émotionnelle **(Wallbott, 1998; Desmet, 2002; Coulson, 2004, Bianchi-Berthouze, 2008)**. De plus, des interjections vocales telles que rires, cris, surprises, bâillements, etc. paraissent au premier abord être de bons exemples d'expressions émotionnelle. Par exemple, une plaisanterie drôle provoque l'amusement, qui produit le rire **(Russell et al., 2003; Ludden, 2008)**. Plus récemment, l'utilisation des signaux physiologiques de l'électromyographie (EMG), la fréquence cardiaque, l'électroencéphalographie (EEG), etc. visant à l'identification des émotions ont été investigués **(Tomino et al., 2008; Jenkins et al., 2009; Alexiou et al., 2009).**

2.3.2 Avantages et inconvénients des approches physiologiques et cognitives

L'approche cognitive est relativement simple, peu coûteuse, et d'application rapide. En particulier l'évaluation subjective à travers des questionnaires et interviews est relativement pratique. Elle amène rapidement des résultats statistiques et les questionnaires sont faciles à administrer. Cependant, l'application des approches cognitives fait aussi l'objet d'inconvénients qui ont été mentionnés dans la littérature. Premièrement, les mesures cognitives ne permettent pas d'évaluer en temps réel. Il devient donc parfois difficile de saisir de manière objective des états émotionnels secondaires ou subtils. D'autre part, l'utilisation des échelles émotionnelles qui se base souvent sur l'utilisation de longues listes d'adjectifs émotionnels peut amener à une certaine *fatigue* des répondants. D'autant plus que certains répondants ont des difficultés à exprimer leurs sentiments parce qu'ils ne sont pas toujours conscients de ces sentiments et qu'ils peuvent être sujets à certains biais sociaux **(Poels & Dewitte, 2006)**.

L'approche physiologique permet de recueillir simultanément des données quantitatives et objectives de manière simultanée et en temps réel **(Tran et al. 2007)**. Des *micro-émotions phasiques* et des modifications de l'attention qui la plupart du temps ne sont pas accessibles à la conscience peuvent être détectées. Cependant, une instrumentation non naturelle, intrusive et lourde peut interférer avec l'activité naturelle des designers et influencer les résultats **(Tran et al. 2007; Ganglbauer et al., 2009)**. Certaines mesures physiologiques ne permettent pas de couvrir une longue durée car elles peuvent causer un échauffement **(Tran et al. 2007)**. Des paramètres environnementaux incontrôlés peuvent générer une excitation ou causer différentes émotions chez les personnes et donc altérer les résultats **(Ganglbauer et al., 2009)**. Enfin, la moyenne globale de la précision des données est de 70-80 %, ce qui n'est pas suffisant **(Ganglbauer et al., 2009)**.

2.3.3 Synthèse: besoin de combiner les méthodes cognitives et physiologiques

Comme nous l'avons mentionné, même si les méthodes physiologiques présentent certains avantages mais aussi inconvénients, l'application de mesures physiologiques menée avec précaution peut apporter des résultats objectifs et prometteurs en conjonction avec les résultats issus des approches cognitives. De plus, ces mesures peuvent permettre de détecter des états émotionnels plus subtils lors de l'activité des designers. Par conséquent, un verrou scientifique subsiste dans la capacité à équilibrer les méthodes cognitives et physiologiques **(Dorst & Dijkhuis, 1995; Coley et al., 2007)** et de développer de nouvelles techniques d'analyse de la perception dites économiques, mobiles et faisables **(Tran et al., 2007)**.

Dans notre contexte, la recherche porte sur les processus cognitifs et affectifs des designers relatifs à l'élaboration des représentations précoces. Ainsi, afin d'extraire l'information mentale et les opérations cognitives associées lors de la génération d'esquisses, une analyse protocolaire a été établie et appliquée. De plus, on peut aussi combiner les approches physiologiques et comportementales afin d'analyser les changements de comportement inconscients qui peuvent survenir chez les designers, par exemple, les changements de signaux physiologiques et les postures/ou mouvements corporels des designers.

Concernant l'évaluation de la réponse émotionnelle des esquisses préliminaires, l'utilisation de mesures cognitives basées sur l'approche du différentiel sémantique a été principalement mise en œuvre dans les domaines du design émotionnel et de l'Ingénierie Kansei. Cependant, afin de pouvoir évaluer de manière continue des états émotionnels secondaires, il est nécessaire de combiner les approches physiologiques avec les approches cognitives. Ces méthodes permettent de quantifier les réactions émotionnelles relatives aux esquisses préliminaires et apportent des résultats objectifs et prometteurs.

Nous avons donc dans le cadre de cette thèse, à travers une étude empirique, employé à la fois des méthodes cognitives et physiologiques afin de formaliser les processus cognitifs et affectifs des designers et identifié les réactions émotionnelles relatives aux représentations précoces.

2.4 Conclusion de l'état de l'art

La section précédente a apporté un état de l'art critique sur l'activité cognitive des designers lors des phases amont du design (§2.1), portant sur l'interaction entre cognition et émotions dans le processus de design (§2.2). Cet état de l'art a montré qu'il existe à la fois des méthodes cognitives et physiologiques afin de mesurer les aspects implicites de l'activité design (§2.3).

Nous avons pu mettre en évidence le manque à combler entre la phase d'information et celle de génération inhérentes aux étapes précoces du design, lors desquelles les designers catégorisent mentalement l'information design afin de générer les esquisses préliminaires. Dans cette thèse, cette phase spécifique a été dénommée ''processus de catégorisation mentale de l'information''. Afin de modéliser un processus global basé sur la cognition et les émotions, il a été nécessaire d'extraire l'information mentale catégorisée et les opérations cognitives associées.

D'autre part, en considérant l'intérêt croissant pour la facette hédonique des produits, les aspects émotionnels inhérents à la relation entre le designer et le produit devraient être pris en compte afin de compléter les aspects cognitifs du design. Etant donné que notre intérêt porte avant tout sur les phases précoces de la conception, la réponse émotionnelle face aux représentations qui y sont relatives constitue aussi d'un grand intérêt. Elle peut nous permettre de comprendre comment les designers injectent des émotions dans les représentations précoces qu'ils élaborent et comment ces représentations elles-mêmes peuvent véhiculer la dimension émotionnelle. Une investigation des méthodes cognitives et physiologiques doit permettre d'identifier et de quantifier les réponses émotionnelles secondaires. Ainsi, les quatre constats majeurs que nous avons répertoriés dans le cadre des recherches actuellement menées sont les suivantes (voir Figure 8) :

- **Constat 1: Besoin de formaliser et d'expliciter un modèle cognitif portant sur la catégorisation mentale mise en œuvre lors des processus informationnels amont;**
- **Constat 2: Considération insuffisante de l'impact émotionnel durant les processus cognitifs des designers;**
- **Constat 3: Considération insuffisante de la réponse émotionnelle relative aux représentations précoces (esquisses);**
- **Constat 4: Besoin de combiner les approches cognitives et physiologiques.**

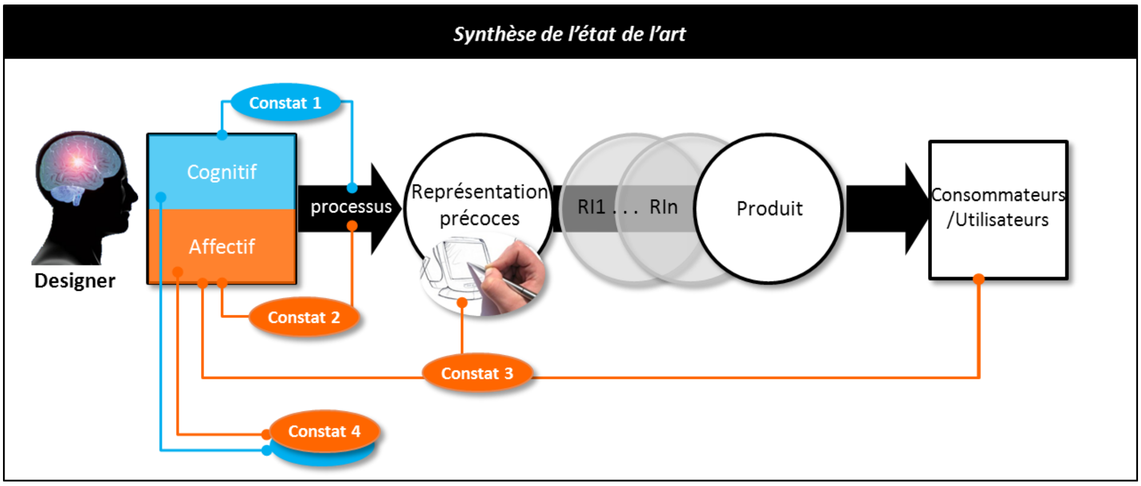


Figure 8101. Synthèse de l'état de l'art

III. PROBLÉMATIQUE ET HYPOTHÈSES DE MODÉLISATION

Le chapitre III propose un énoncé de la problématique et un développement des hypothèses de cette thèse. La problématique a été établie à partir d'un état de l'art portant sur les aspects cognitifs et affectifs du design, et d'un récapitulatif sur les méthodes de mesure cognitives et physiologiques issues de la littérature

3.1 Problématique

Sur la base des quatre constats des recherches discutés dans la section 2.4, nous avons établi la problématique suivante: **''comment modéliser les processus cognitifs et affectifs des designers dans les phases amont de la conception, et plus précisément, durant le processus de catégorisation mentale de l'information réalisé lors de la phase générative?''**. La phase générative est caractérisée par la production d'esquisses jusqu'à l'aboutissement à la ''bonne forme'' d'un ou plusieurs concept(s).

Etant donné que les phases précoces de la conception sont aussi considérées comme parmi les plus intenses d'un point de vue cognitif, plusieurs recherches ont peu à peu investigué cette question afin de formaliser et de développer un modèle explicite de ces phases. Cependant, comme la plupart des recherches menées à ce jour portent plus sur les processus explicites relayés par une information externalisée, il y a un manque à combler entre la phase informative et les phases génératives précoces qui sont relativement implicites dans cette thèse. Nous avons appelé cet espace encore indéfini 'processus de catégorisation mentale de l'information'.

Il nous a semblé nécessaire de développer un modèle cognitif selon lequel les designers catégorisent mentalement l'information design. D'autre part, étant donné que les aspects hédoniques du produit s'avèrent constituer l'une de ses dimensions majeures, l'accent devrait être aussi porté sur les processus affectifs afin de comprendre comment les designers arrivent à intégrer la dimension émotionnelle en générant des représentations, et comment cette dimension émotionnelle pourrait être anticipée en travaillant sur les représentations les plus précoces. Il est à noter que les esquisses correspondent à la toute première externalisation des représentations mentales lors des phases génératives; nous avons fait l'hypothèse que ce type de représentations peut révéler très tôt l'intention des designers, et qu'elles peuvent jouer un rôle dans la prédiction de la réponse émotionnelle auprès des consommateurs.

En synthèse, dans cette thèse, nous avons eu pour objectif de formaliser et développer un modèle de processus cognitif et affectif des designers, à travers la compréhension de leurs processus mentaux et de leur relation avec les représentations précoces (esquisses). D'autre part, vis-à-vis de préoccupations plus industrielles, ce modèle a permis d'extraire des spécifications concrètes pour le développement d'un outil computationnel dédié spécifiquement à cette phase. Ce type d'outil devrait nous conduire, à terme, à une numérisation et une optimisation progressive du processus de conception dans son ensemble.

3.2 Hypothèses de modélisation

Afin de répondre à notre problématique, deux grandes hypothèses ont été explorées (voir Figure 9):

HYP 1: Les processus cognitifs et affectifs des designers, lors desquels les designers catégorisent mentalement l'information design, peuvent être modélisés.

HYP 2: La réponse émotionnelle vis à vis des représentations précoces (esquisses) devrait être formalisée afin de prédire les réactions émotionnelles à partir des phases amont de la conception.

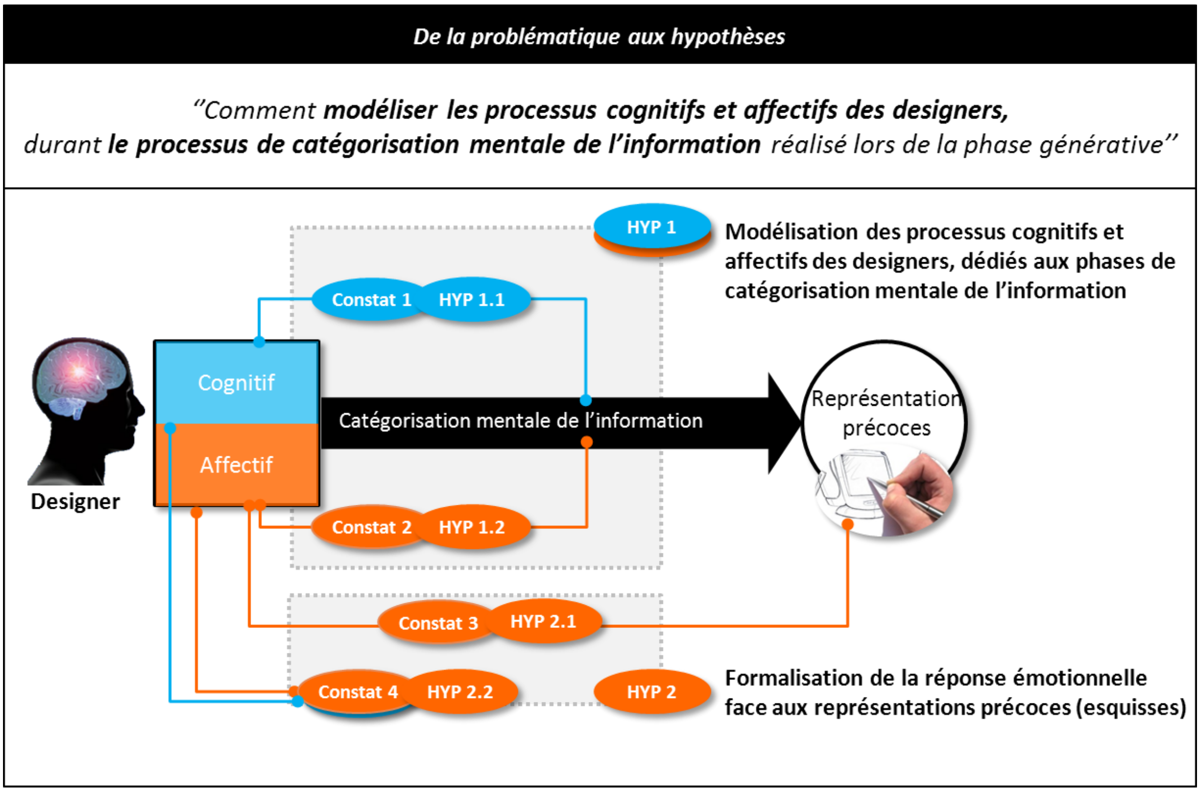


Figure 9. De la problématique aux hypothèses

3.2.1 HYP 1: Modélisation des processus cognitifs et affectifs des designers, dédiés aux phases de catégorisation mentale de l'information

L'HYP 1 porte sur la formalisation conjointe des aspects cognitifs et affectifs des designers, lorsqu'ils catégorisent mentalement l'information design dans la phase générative. L'HYP 1 a été divisée en deux sous hypothèses (HYP 1.1 et HYP 1.2)

HYP 1.1 : Les processus cognitifs des designers, lors desquels les designers catégorisent mentalement l'information design, peuvent être modélisés.

Afin de procéder à cette modélisation, il est nécessaire d'extraire l'information implicite qui est en mémoire et d'identifier les types d'opérations cognitives présents pour comprendre comment l'information design est peu à peu transformée et catégorisée durant les phases précoces de la conception. Ainsi, nous avons d'abord souhaité proposer un modèle descriptif du traitement de l'information qui intègre les modèles mnémoniques issus de la psychologie cognitive: ceux d'**Atkinson & Shiffrin (1968)** et de **Baddeley et al. (2010)** (voir Figure 5) dans la section 2.1.3. L'intégration de ces modèles a été particulièrement pertinente dans le cadre de notre recherche car il existe des mécanismes similaires de catégorisation mentale de l'information relatifs à la mémoire long-terme (LTM) et à la mémoire de travail/court-terme (MT/MCT) dans la pratique des designers. L'information design consiste en différents niveaux. Nous en avons défini trois: haut-niveau (valeur, descripteur sémantique, analogie, style), moyen-niveau (nom de secteur, contexte, fonction) et bas-niveau (couleur, forme, texture). La cohérence s'applique à la fois sur la prise en compte croisée de ces différents niveaux et sur chacun de ces niveaux pris indépendamment. De plus, l'information stockée dans notre mémoire long-terme (LTM) se structure autour de *réseaux de nœuds et de liens*. Un nœud peut contenir des concepts, mots, images, ou toute autre information, et les liens représentent l'association entre différents nœuds. Ces associations portent aussi sur différents niveaux de traitement haut- et bas- niveau comme nous l'avons observé dans le cadre de la pratique du design.

Sur la base de notre modèle descriptif de traitement de l'information, nous avons sélectionné principalement six opérations cognitives à prendre en compte lors du traitement de l'information dans sa globalité: *l'attention sélective*, *l'attention visuo-spatiale*, le *questionnement*, *l'association*, la *transformation*, et le *jugement/décision*. Ces six opérations cognitives et les trois niveaux d'information (haut/moyen/bas) ont été utilisés afin de définir une grille de codage pour extraire des données quantitatives sur la manière dont les designers transforment mentalement ou catégorisent l'information durant les phases amont de la conception.

HYP 1.2 : Les réactions émotionnelles des designers entrent en jeu lors des processus cognitifs en générant les stimuli et aussi en évaluant les résultats durant la phase générative.

Bien que l'analyse des processus cognitifs des designers soit d'un intérêt crucial pour la recherche en design et pour la pratique de cette spécialité (HYP 1.1), il est important de ne pas oublier l'importance des aspects émotionnels qui viennent les compléter. Les processus affectifs des designers peuvent ainsi apporter des indices afin de mieux comprendre comment les designers intègrent une dimension émotionnelle à travers leurs solutions design, et comment ces solutions sont ensuite perçues par les consommateurs. Sur la base d'un état de l'art relatif à la cognition et aux émotions en design décrit dans la section 2.2.2, il nous a semblé important de comprendre les processus affectifs des designers en générant les stimuli et aussi en évaluant les résultats durant la phase générative. 'L'impact émotionnel relatif à la génération' joue un rôle dans la régulation du traitement de l'information mentale en activant l'information nécessaire ou en faisant varier l'attention de manière à s'adapter à la tâche en cours. D'autre part, 'L'impact émotionnel relatif à l'évaluation' provoque le jugement ou l'évaluation des idées ou des designers eux-mêmes. L'impact réciproque lors de ces deux types de taches peut avoir une relation et une influence forte sur les processus cognitifs lors des phases amont du design. Il est nécessaire de mener des analyses complémentaires afin de compléter les résultats qui viendront étayer cette hypothèse.

3.2.2 HYP 2 : Formalisation de la réponse émotionnelle face aux représentations précoces (esquisses)

Alors que l'HYP 1 concerne les aspects cognitifs et émotionnels des designers durant le processus de catégorisation mentale de l'information dans la phase générative, l'HYP 2 établit la relation entre les aspects émotionnels des designers et les représentations.

HYP 2.1: ***La réponse émotionnelle vis à vis des représentations précoces (esquisses) peut être identifiée à partir des phases précoces du design.***

Un lien peut être établi entre cette réponse recueillie à partir d'esquisses et le même type de réponse obtenue à partir de produits. De cette manière il est peut être possible d'anticiper la réponse du consommateur. Dans la communauté des sciences de la conception, nous pouvons noter un intérêt croissant pour le design émotionnel. Afin d'améliorer la dimension émotionnelles du produit, il est nécessaire d'identifier la réponse émotionnelle vis à vis des représentations précoces générées lors des phases amont du design. Etant donné que les designers débutent à partir de leurs représentations mentales, les esquisses préliminaires correspondent à la toute première externalisation de l'information mentale dans la phase générative. Dans notre contexte, la réponse émotionnelle aux esquisses préliminaires constitue un intérêt fort. Plusieurs recherches ont été menées afin d'évaluer les esquisses préliminaires, mais ces évaluations ont plus porté sur la créativité des concepts représentés. A ce jour, il n'y a pas eu de recherche représentative, à notre connaissance, qui investigue la notion d'émotions provoquées à travers les esquisses préliminaires. Sur la base de ces arguments, nous avançons l'hypothèse suivante :

HYP 2.2 Quantification de la réponse émotionnelle en combinant les approches cognitives et physiologiques

En complément de l'HYP 2.1 ci-dessus, l'HYP 2.2 pose la question des méthodes les plus pertinentes à sélectionner ou à définir et à mettre en œuvre afin de quantifier la réponse émotionnelle relative aux représentations précoces. Dans de nombreux cas, les approches cognitives ont été largement appliquées afin de quantifier la réponse sémantique et émotionnelle vis à vis du produit. Cependant, l'approche cognitive ne permet pas d'évaluer la réaction émotionnelle en temps réel. Et il est difficile de saisir de manière objective un état émotionnel subtil tel qu'une émotion secondaire. De plus, la réponse émotionnelle est difficile à exprimer sous forme lexicale. Afin de prendre en compte les limites relatives aux approches cognitives, des recherches récentes ont commencé à combiner ces approches avec les méthodes physiologiques. Il est probable qu'une instrumentation non naturelle et intrusive puisse interférer avec les comportements naturels des répondants et influencer les résultats; cependant, l'application de mesures physiologiques prise de manière précautionneuse peut améliorer notre compréhension des phénomènes émotionnels inconscients des répondants **(Tran et al., 2003; Ganglbauer et al., 2009)**.

Ainsi, le croisement des résultats de l'approche cognitive et de l'approche physiologique nous a permis de quantifier la réponse émotionnelle vis-à-vis des esquisses préliminaires. Nous avons souhaité compléter les résultats issus de l'approche cognitive en obtenant des informations plus précises sur les émotions secondaires provoquées par les esquisses préliminaires. En effet les méthodes physiologiques apportent une information continue ainsi que des informations sur les états émotionnels inconscients qui sont difficiles à appréhender.

IV. EXPÉRIMENTATIONS

Dans le chapitre IV, deux expérimentations ont été proposées afin de tester les hypothèses spécifiques développées dans le chapitre III. La première expérimentation (EXP 1) a visé à décrire comment les designers catégorisent mentalement l'information design durant les phases génératives précoces, soit celles de génération d'esquisses. Le but de la deuxième expérimentation (EXP 2) a été d'identifier la réaction émotionnelle à travers les représentations précoces (esquisses). Chaque sous-section comporte des résultats et une discussion. Finalement, cette section se conclue par la validation des hypothèses de recherche.

Introduction

Dans le chapitre IV, deux expérimentations ont été proposées afin de tester des hypothèses développées dans la section 3.2 (voir Figure 10).

L'expérimentation 1 (EXP 1) a permis de répondre à l'HYP 1 et aux sous-hypothèses associées (HYP 1.1 + HYP 1.2). Cette expérimentation a eu pour but de décrire comment les designers catégorisent mentalement l'information durant les étapes précoces de génération d'esquisses réalisées dans la phase générative. Nous avons élaboré et conduit une analyse protocolaire avec seize designers produit sur la base d'un modèle descriptif dérivé des théories sur la mémoire issues de la psychologie cognitive (voir Figure 5). Notre champ expérimental a été principalement le projet GENIUS, dont la finalité était de développer un outil logiciel pour supporter l'activité des designers dans les phases précoces de la conception.

L'expérimentation 2 (EXP 2) a porté sur l'HYP 2 et les sous-hypothèses associées (HYP 2.1 + HYP 2.2). Le but de cette expérimentation a été d'identifier la réaction émotionnelle face aux premières représentations qui sont généralement les esquisses. Cette expérimentation a aussi permis d'investiguer comment les méthodes cognitives et physiologiques peuvent être combinées et appliquées dans le cadre de nos recherches afin de quantifier la réponse émotionnelle vis-à-vis des esquisses préliminaires.

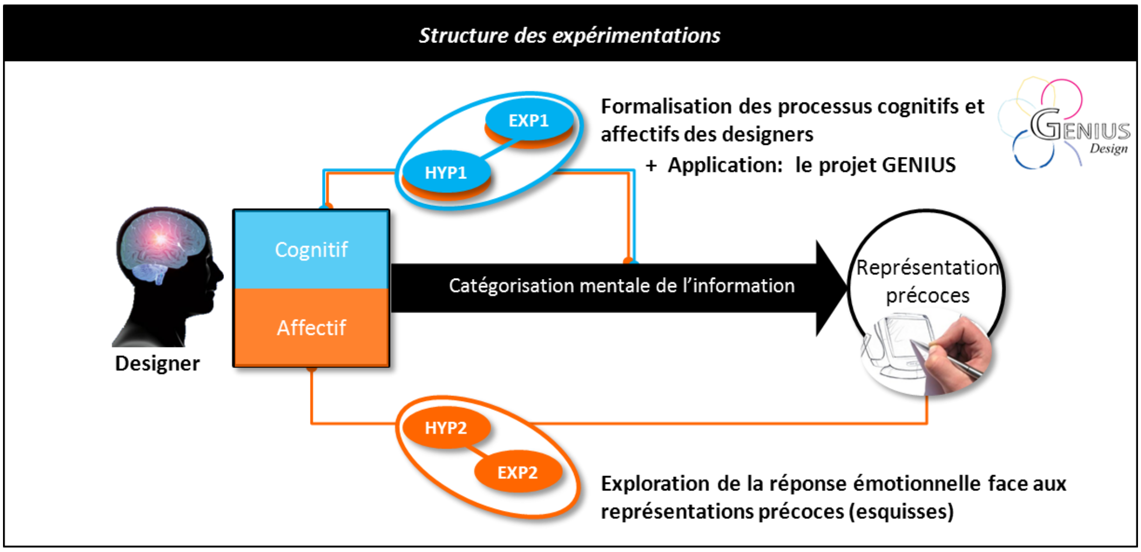


Figure 102. Structure des expérimentations

4.1 EXP 1: Formalisation des processus cognitifs et affectifs des designers

4.1.1 Objectifs

Le but de l'EXP 1 a été de décrire les processus cognitifs et affectifs des designers, qui interviennent lors de la catégorisation mentale de l'information dans la phase générative (voir Figure 11).

Les objectifs étaient:

- de quantifier quel types d'informations mentales sont extraits et comment ces informations sont transformées et catégorisées à travers des opérations cognitives spécifiques durant les phases de génération d'esquisses;
- d'explorer les processus affectifs des designers qui entrent en jeu et interagissent avec les processus cognitifs en générant les stimuli et aussi en évaluant les résultats durant la phase générative;
- d'identifier des similarités et des différences dans l'activité design entre des designers novices ou experts.

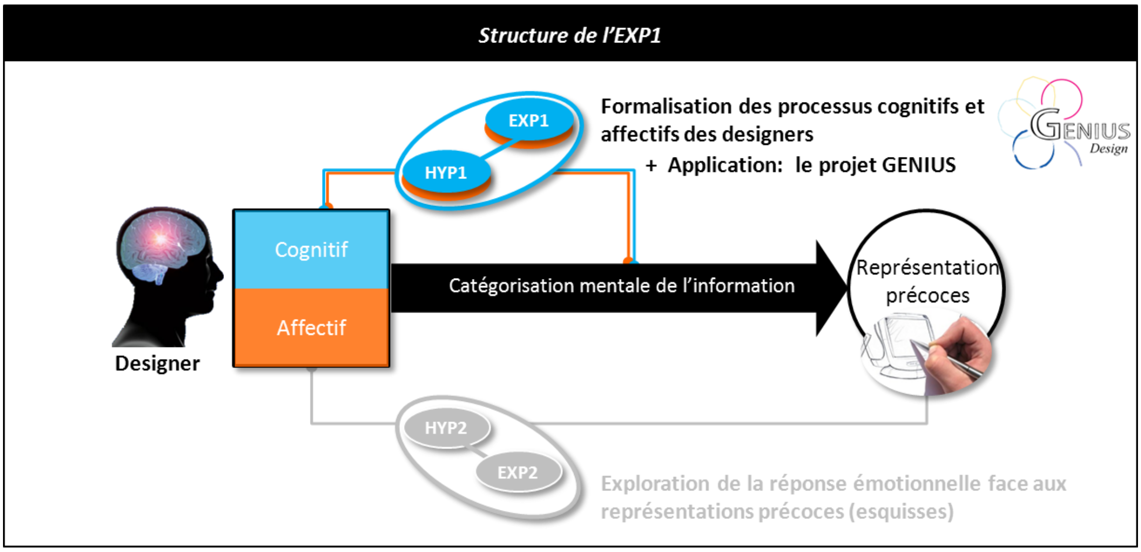


Figure 103. Structure de l'EXP 1

4.1.2 Méthode

Concernant les méthodes de recueil de l'information auprès des designers, différentes approches ont vu le jour. Dans notre cas, l'objectif était d'identifier la nature de l'information et les opérations cognitives qui entrent en jeu, avec leur relation vis à vis des différents types de mémoire, sensorielle, de travail et long-terme **(Dorst & Dijkhuis, 1995; Lloyd et al., 1995; Kim et al., 2009a)**. Nous avons choisi d'appliquer la méthode de raisonnement à voix haute qui semblait appropriée pour formaliser des processus cognitifs implicites **(Ericsson & Simon, 1993; Dorst & Dijkhuis, 1995; Gero & Tang, 2001; Bilda, 2006; Coley et al., 2007; Cross, 2008;).** Nous avons réalisé trois tests pilotes qui nous ont permis de valider l'efficacité de cette méthode et le type de consigne (brief du design) dans notre contexte. Cependant nous avons intégré dans le protocole final des interviews semi-directifs, afin de pallier aux possibles déficiences relatives à l'interprétation des données produites dans le cadre de l'approche de raisonnement à voix haute **(Lindlof & Taylor, 2002)**. Nous souhaitions ainsi vérifier que ce type de recueil ne biaise pas l'activité en cours lors des phases génératives et permet un recueil relativement complet de l'information **(Davies, 1995; Lloyd et al., 1995; Kim et al., 2009a)**. Les interviews semi-directifs ont consisté à réutiliser les esquisses et commenter le cheminement des idées et opérations à partir de ces esquisses.

4.1.2.1 Participants

16 designers ont participé au test, dont 8 experts avec une moyenne de 10,3 ans d'expérience, et 8 novices (10/8 HF).

4.1.2.2 Matériels et déroulement

L'EXP 1 s'est déroulée sur le lieu de naturel travail des designers avec les moyens habituels de formalisation et de représentation de solutions design. L'observation a été réalisée avec deux caméscopes (une pour mesurer la gestuelle relative aux esquisses au niveau des membres supérieurs, et l'autre pour avoir une vue d'ensemble du designer), et un enregistreur vocal afin de recueillir les verbalisations des participants (voir Figure 12).

L'étude a été réalisée en trois étapes :

1. Description de l'expérimentation et entrainement (vis-à-vis de la méthode think-aloud) (15mn) ;
2. Pensée à voix haute tout en réalisant des esquisses à partir d'un cahier des charges fictif (dessiner l'aspirateur Nike) (60mn) ;
3. Interviews semi-directifs au sujet des images mentales, des descripteurs sémantiques utilisés, des formes générées et de la relation entre ces trois types de données (15mn).

Figure 12. Equipements (Kim et al., 2009b)

4.1.2.3 Analyse des données: processus de codage

La plupart des méthodes d'analyse divisent l'ensemble du protocole en unités qui correspondent à des segments qui sont ensuite codés selon une grille de codage appropriée **(Goldschmidt, 1991; Suwa et al., 1998; Kim et al., 2009b, 2010a)**. Les enregistrements vidéo produits lors de la génération d'esquisses ont aussi été utilisés afin de consolider avec plus de précision les résultats des verbalisations. Chaque unité de séquence de texte a été manuellement indexée aux intervalles vidéos correspondants, avec le logiciel d'analyse vidéo INTERACT qui permet ensuite l'analyse statistique des résultats **(INTERACT, 2009)**. Notre schéma de codage inclue trois catégories: information design, opérations cognitives et expressions vocales (voir Tableau 2).

D'abord, la grille de codage a été basée sur une structuration du contenu verbal de l'information design sur le travail mené précédemment dans le cadre du projet TRENDS **(Bouchard et al., 2007, 2009)**. Le codage du type d'information a été établi sur la base du Tableau 2 selon les trois niveaux (Haut, Moyen, Bas) et les 10 catégories (Valeur, Descripteur sémantique, Analogie, Style, Nom de secteur, Contexte, Fonction, Couleur, Forme et Texture). D'autre part, nous avons répertorié les opérations cognitives qui permettent de relier et de traiter ces différents types d'informations **(Kim et al, 2010a)**. Le Tableau suivant présente ces opérations qui retracent l'ensemble du processus cognitif lors de la production d'esquisses dans sa globalité. On trouve ainsi les opérations d'attention sélective ou visuo-spatiale, de questionnement, d'association (ascendante, descendante ou équi-niveau), de transformation et de jugement orienté vers la décision. L'ensemble du codage pour les opérations cognitives que nous avons définies est répertoriées en Annexe A. Le schéma de codage pour les expressions vocales a été développé à partir des travaux de **Russell (2003),** de **Reisenzein et al. (2000),** et de **Ludden (2008).** Il intègre les notions de d'acquiescement, de surprise, de rire, et d'incertitude. Chaque expression vocale peut être reliée à un état émotionnel spécifique. Le schéma complet du codage permet de comprendre les connexions entre les représentations mentales et le rappel d'informations externes durant la génération d'esquisses. Il apporte une description des processus cognitif et affectif qui entrent en jeu lors de la catégorisation de l'information design.

Tableau 2. Trois codages de l'information design, des opérations cognitives, et des expressions vocales

Catégories		Description	Exemples
Codage de l'information design (Bouchard et al., 2008, 2009; TRENDS D2.3, 2009)			
Haut niveau (HN)	Valeur	Ces mots représentent des valeurs finales ou comportementales	Sécurité, Bien-être
	Descripteur sémantique	Les descripteurs sémantiques sont souvent des adjectifs qui réfèrent à des dimensions affectives (domaine du Kansei)	Romantique, Agressif
	Analogie	Objets d'autres secteurs avec des traits intégrés dans le secteur de référence (morphings)	Lapin → rapide
	Style	Caractéristiques tous niveaux à travers un style spécifique	Edge Design
Moyen niveau (MN)	Nom de secteur	Noms d'objets décrivant un secteur ou un sous-secteur représentant une tendance particulière	Sport
	Contexte	Utilisateur cible et contexte d'utilisation	Loisirs, familial
	Fonction	Fonction, usage	Modularité
Bas niveau (LN)	Couleur	Propriétés chromatiques	Jaune, bleu clair
	Forme	Combinaison de forme, composant de forme, taille	Carré, ondulé
	Texture	Motifs (abstrait ou figuratif) et textures	Plastique, métallique
Codage des opérations cognitives (Finke et al., 1992; Harris, 1992; Suwa et al., 1998; Ball & O'callaghan,2001; Style, 2005)			
Attention sélective		Se concentrer de manière sélective en sollicitant les sens externe ou interne	(En regardant un objet dans l'espace expérimental) cette forme m'a pensé à quelque chose.
Attention visuo-spatiale		Attention visuo-spatiale des caractéristiques des éléments représentés sur l'esquisse	Vu de profil, il faut que mon écran il soit un petit peu orienté vers l'utilisateur.
Questionnement		Auto-questionnement à propos d'idées émergentes sans référer à un autre niveau d'information	Est ce que ça fait sportif ?
Association		Association d'information descendante en conservant l'idée (descendant/ascendant/équi-niveau)	On est sur un aspirateur d'appoint donc quelque chose de rapide, avec de la vitesse.
Transformation		Transformer une idée origine par analogie	Il y a l'aspirateur automatisé, comme une espèce de robot.
Jugement		Jugement orienté vers la décision et vers la solution en cours de définition	Ah cette poignée est trop classique ce n'est pas bon!
Codage des expression vocale (Reisenzein et al., 2000; Russell, 2003; Ludden, 2008)			
Acquiescement		Réflexion les réponses cognitives vis à vis des solutions	'aha', 'Ah,oui' , 'ok', 'ca y est'.
Surprise		Sons aux mots qui réfèrent à la surprise	'oh', 'wow', 'super'
Rire		Ressentir du ''fun'' et de l'amusement	'haha', rigolo, 'marrant'
Incertitude		Ne pas être sur	'well, hmm', 'Je ne sais pas'

4.1.3 Résultats et discussion

- ***Cartes de catégorisation d'idées***

Dans le but d'examiner quels types d'informations mentales ont été extraits et comment celles-ci ont été transformées ou catégorisées pendant l'élaboration des esquisses préliminaires, des cartes de catégorisation des idées sont présentées en tant que résultats de l'analyse. Ces cartes sont composées des mots clés issus des verbalisations et des représentations externes. Un exemple de carte est présenté ci-dessous, correspondant à la synthèse d'activité cognitive pour un designer (voir Figure 13).

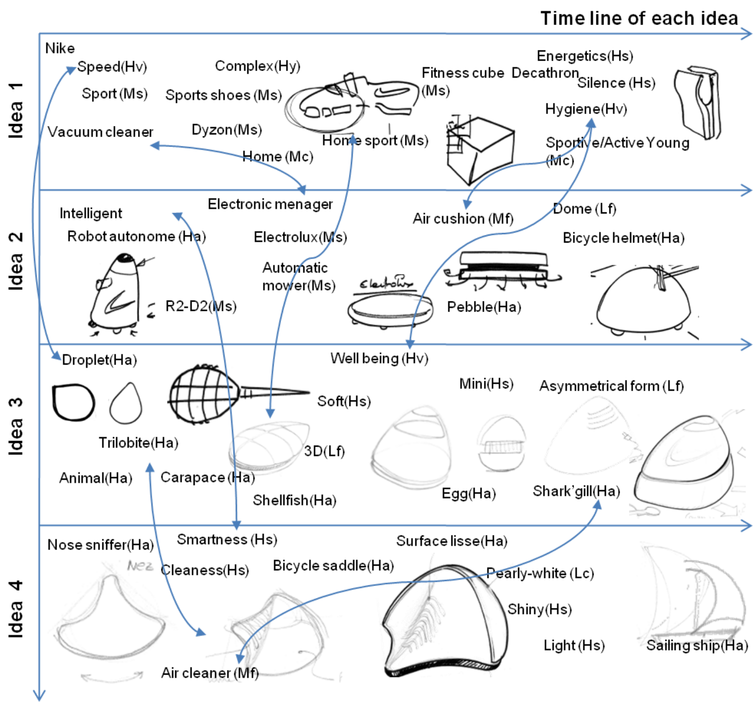
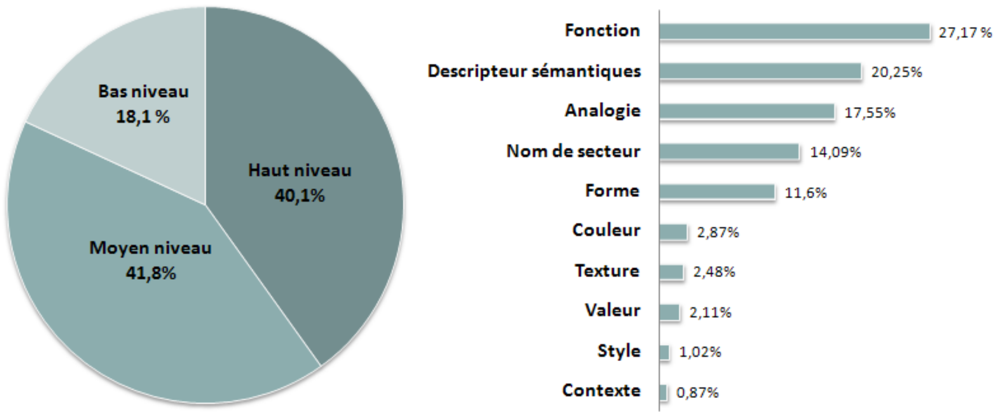


Figure 13. Carte de catégorisation des idées pour le concepteur 5 (Kim et al., 2009b)

Le raisonnement mental est révélé par les cartes de catégorisation. L'axe X représente les variations et les transformations observées autour d'une idée, alors que l'axe Y représente le temps global pendant lequel est réalisée la tâche et montre en particulier le passage d'une idée à l'autre. Les flèches représentent les séquences suivies par le concepteur lors de la génération des esquisses. En résumé, ces résultats qualitatifs ont trois types d'implications. D'abord, une série d'opérations cognitives engagées par le designer lui-même a été mise en évidence. Ces opérations interviennent dans le cadre d'itérations entre les esquisses et les informations mentales en appliquant des transferts analogiques ou de références multiples. Ils permettent de transformer une idée ou de passer d'une idée à une autre. Deuxièmement, lors de la génération d'esquisses, le designer peut renforcer ses idées avec des mots clés (descripteurs sémantiques) ou des exemples de produits existants. Troisièmement, nous avons analysé grâce aux cartes de catégorisation la continuité et la discontinuité du flux des idées. Nous faisons l'hypothèse qu'il existe certains catalyseurs qui permettent de relier les informations mentales entre elles. Cette comparaison entre les idées précédentes et les idées courantes peut aider dans le processus d'évaluation et de décision.

- ***Structure et contenu de l'information***

L'information de type moyen-niveau est celle qui a été utilisée le plus fréquemment (41,8%), vient ensuite de l'information haut-niveau (40,1%) plus bas-niveau (18,1%). Ainsi, les informations de type haut-moyen niveau ont été utilisées à 81,9% selon les termes énoncés pendant la tache de génération d'esquisses. L'information de type bas-niveau a été représentée plutôt sous la forme des esquisses qu'à travers les verbalisations. Le détail des fréquences recueillies pour chacune des catégories est présenté Figure 14. Le contenu verbalisé le plus fréquemment est du registre de la fonction (27,2%); il est suivi de près par les descripteurs sémantiques (20,3%). Les huit catégories restantes ont été mentionnées relativement moins fréquemment.



(a) *(b)*

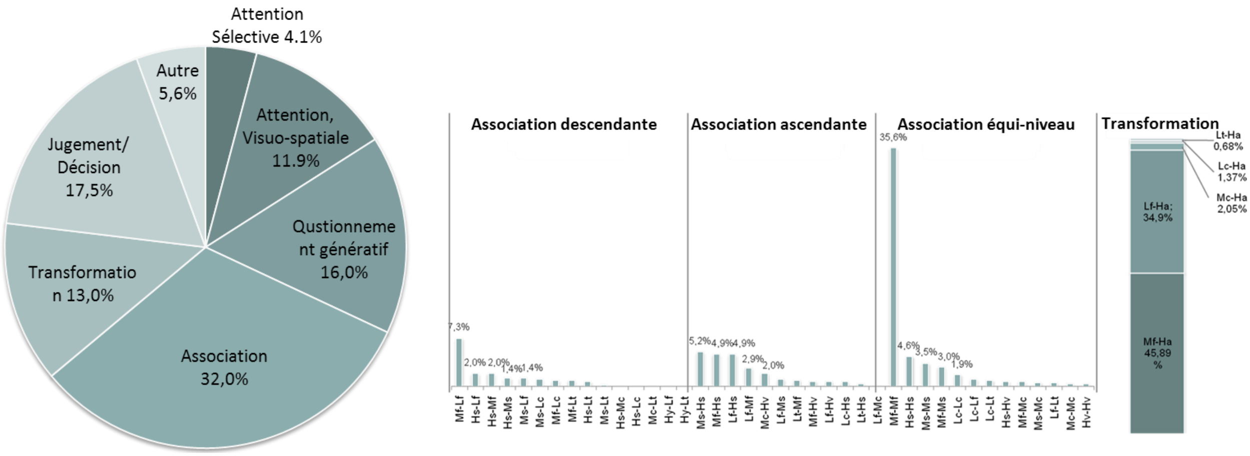
Figure 14. Pourcentage d'occurrences pour chacune des catégories d'information design

Le contenu de verbalisations faites par les designers était très dépendant du cahier des charges design: *Concevoir l'aspirateur Nike*. Par exemple, les mots les plus représentatifs de la catégorie valeurs ont été ''*dynamisme''* et ''*esthétique''*, et les descripteurs sémantiques les plus communs ont été *sportif*, *dynamique*, *fluide*, *classique*, *technique*, *fun*, *gentil*, etc. Les designers ont aussi employé une douzaine d'analogies qui ont référée, par exemple, aux sports (l'utilisation d'un harnais ou d'un scooter, en soulevant des poids, en utilisant des nageoires, le vélo, la danse, etc.), au biomorphisme (animaux (requin), humains (bouche) et plantes), aux chaussures et à la bagagerie (sac à dos, accessoires, etc.). Ces références ont tiré lourdement les associations sémantiques et conceptuelles avec la marque Nike (par ex: les produits industriels, les appareils électriques électroménagers utilisés pour la protection et le conditionnement d'air, les robots, les récipients et les biens immobiliers). La catégorie couvrant les fonctions du produit visé a été composée de réponses rattachées à sa mécanique interne, aux unités et aux utilisations ou à des opérations telles "ventiler", “épousseter le sac”, "coussin pneumatique", etc.

- ***Opération cognitives***

La Figure 15a montre la fréquence d’apparition des différentes opérations cognitives. En moyenne, l’opération d’*association* a compté pour 32,0% de l’ensemble des opérations cognitives, le jugement et la décision pour 17,5%, le *questionnement* pour 16,0%, la *transformation* pour 13,0%, l’*attention visuo-spatiale* pour 11,9%, et l’*attention sélective* pour 4,1%. Pendant la phase générative, les designers ont exercé plus d'effort afin de produire des idées en rappelant des informations design stockées dans leur mémoire. Le processus de rappel s’est basé sur différentes opérations d’association/transformation/questionnement, représentant au total 61,0% de l’ensemble des opérations cognitives. Ainsi, le jugement et la décision ont été sollicités moins fréquemment que l’opération d’association. De plus, l’attention sélective a rarement été mise en œuvre pour inspirer les réponses, du fait que l’expérimentation a surtout été focalisée sur le rappel des informations en mémoire en éliminant les stimuli externes et en encouragent les designers à ne référer qu’à leur mémoire seule durant la tâche en cours. D’autre part, à cause de l’intérêt important que nous avons porté sur les opérations cognitives relatives au processus de rappel, nous avons affiné le codage relatif aux opérations d’association et de transformation en sous-catégories de l’information design (cité Annexe A). Selon les trois niveaux d’information que nous avons défini, l’information design peut être associée de trois manières: association descendante (de concrète à abstraite), association ascendante (de abstraite à concrète), ou association équi-niveau.

Une analyse plus détaillée des résultats a montré une pluralité de 32,0% des réponses relatives aux associations avec essentiellement des associations de type équi-niveau (17,6%) entre des fonctions (Mf–Mf), des descripteurs sémantiques (Hs–Hs), ou des noms de secteurs (Ms–Ms). En deuxième position arrivent les associations ascendantes (8,7%) et descendantes (6,7%). La Figure 15b montre la fréquence de chaque sous-catégorie d’association. La plupart des associations ascendantes sont de type moyen à haut-niveau (M→H), en référence aux relations entre les fonctions et les descripteurs sémantiques (Mf–Hs), ou bas à haut-niveau (L→H), en référence aux relations entre les descriptions de forme et les descripteurs sémantiques (Lf–Hs). Les associations descendantes représentatives incluent la relation entre les fonctions et les descriptions de forme (Mf–Lf) ou l’utilisation de descripteurs sémantiques pour décrire la forme (Hs–Lf). En faisant appel à l’opération cognitive de transformation, les designers ont créé de nouvelles idées intéressantes et de nouveaux concepts en formant des analogies avec des fonctions (Mf–Ha, 45,9%) ou descriptions de forme (Lf–Ha, 34,9%) (voir Figure 15c). Dans la section 5.1, la relation entre les opérations d'*association* et de *transformation* sera approfondie et présentée au sein d'un modèle cognitif des processus de catégorisation mentale de l'information.



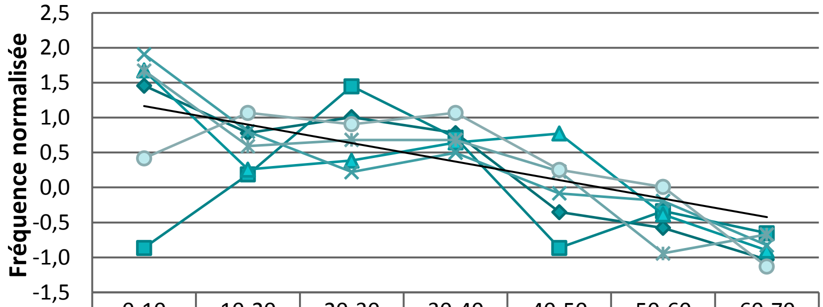
(a) (b) (c)

Figure 15. (a) Opérations cognitives engagées lors de la session, (b) association descendante/ascendante/équi-niveau, (c) transformation

- ***Progression des opérations cognitives dans le temps***

Nous avons répertorié le nombre total d'opérations cognitives présentes selon des intervalles toutes les 10 mn afin d'observer les évolutions et les changements concernant les 6 opérations cognitives. Selon **Bilda & Gero (2008)**, la fréquence normalisée d'observation des opérations cognitives est calculée selon la formule [Normalisée_A = (A – moyenne)/ écart type]. Comme le montre la figure ci-dessous, si la part d'une opération cognitive est montante, la fréquence normalisée a une valeur positive, et si l'opération cognitive est décroissante, elle a une valeur négative (voir Figure 16).

Nous avons observé deux groupes différents d'opérations cognitives qui suivaient tous les deux la même tendance. Un groupe comportait les opérations d'*association*, de *transformation*, de *questionnement* et d'*attention sélective* et l'autre groupe était constitué des opérations d'*attention visuo-spatiale* et de *jugement/décision*. Pendant les premières 10 minutes, une variance négative a été observée pour *l'attention visuo-spatiale*, cela peut être du au fait que les designers ont tendance à rappeler massivement des informations qu'ils ont catégorisé mentalement et qui sont stockées dans leur mémoire lors des phases amont du processus de design. Après un bref intervalle, les designers ont commencé à générer les esquisses préliminaires afin de représenter leurs idées tout en évaluant l'écart perçu par rapport à leur objectif. Pour cette raison, nous avons pu rapprocher l'opération de jugement/décision et de l'attention visuo-spatiale.



	0-10 mins	10-20 mins	20-30 mins	30-40 mins	40-50 mins	50-60 mins	60-70 mins
Attention sélective	1,5	0,8	1,0	0,8	-0,4	-0,6	-1,0
Attention visuo-spatiale	-0,9	0,2	1,4	0,7	-0,9	-0,3	-0,7
Questionnement	1,7	0,3	0,4	0,6	0,8	-0,4	-0,9
Association	1,9	0,8	0,2	0,5	-0,1	-0,2	-0,8
Transformation	1,7	0,6	0,7	0,7	0,2	-0,9	-0,7
Jugment/ Décision	0,4	1,1	0,9	1,1	0,3	0,0	-1,1

Figure 16. Fréquence normalisée de chaque opération cognitive toutes les 10 mn

- ***Processus affectifs des designers***

Afin d'identifier les réactions émotionnelles des designers qui entrent en jeu durant les processus cognitifs, nous avons collecté et analysé les expressions à la fois linguistiques et non linguistiques lors des verbalisations simultanées. Particulièrement, les dernières semblent très importantes dans l'analyse des réactions émotionnelles qui ne peuvent pas être extraites simplement à partir de données lexicales. De plus les réactions non linguistiques permettent aussi de recueillir des réactions émotionnelles secondaires. Le Tableau 3 montre le nombre total d'expressions vocales utilisées par les 16 designers durant la phase générative. Les designers ont tendance à utiliser des termes d'acquiescement concernant les solutions ou la tâche elle-même, tels que 'aha', 'oh oui', etc. dans plus de la moitié des expressions verbales, lorsqu'une nouvelle information ou qu'une nouvelle idée arrive dans le processus de génération. Ensuite, des expressions vocales telles que 'l'incertitude', 'la surprise exprimée par la voix', ou 'le rire' ont suivi.

Tableau 3. Nombre total of d'expressions vocales exprimées par les 16 designers produit

	Expressions vocales				
	Acquiescement	Surprise	Rire	Incertitude	Total
8 Experts	51	14	12	12	89
8 Novices	32	8	4	25	69
Total	83	22	16	37	158

Comme le montre la Figure 17, nous avons aussi observé de nombreuses gestuelles et expressions faciales des designers durant la phase générative. Cependant, il a été relativement difficile de quantifier les résultats car les designers ont baissé la tête pendant la production des esquisses afin d'observer le résultat en temps réel.

Figure 104. Exemples de gestuelles et d'expressions faciales des designers

- ***Différences entre novices et experts***

En terme de taux d'opérations cognitives et de structure de l'information design, il y a des différences significatives entre les designers experts et novices.

Concernant les processus affectifs (voir Tableau 3), nous avons pu voir que les designers tendent à utiliser des expressions vocales de type affirmatif, et qu'ils sont souvent sujets à la surprise ou à l'amusement durant la phase générative. En comparaison, les designers novices ont l'habitude d'utiliser plus de termes affirmatifs lorsqu'ils évaluent leur résultat ou la tâche elle-même. Ils ont tendance à plus faire plus preuve d'incertitude dans les catégories d'expressions vocales. D'autre part, concernant les conditions méthodologiques de 'verbalisation simultanée', les résultats de l'analyse de type ANOVA ont montré que les designers experts verbalisent plus facilement de manière simultanée pendant la réalisation des esquisses et l'annotation, que les designers novices (F critique = 0,02, P=0,48).

4.1.4 Conclusion/validation de l'HYP 1

Pendant l'EXP 1, nous avons eu pour objectif de décrire les processus cognitifs et affectifs des designers, lors de la catégorisation mentale de l'information inhérente à la phase générative. Cet objectif visait à répondre à l'HYP 1 et aux sous-hypothèses relatives à la partie 3.2.

Les trois types de résultats obtenus (qualitatifs, quantitatifs et intégrés) ont démontré que: (1) la structure de l'information design, les analogies fonctionnelles et structurelles aussi bien que les liens entre les fonctions, les descripteurs sémantiques, et les descriptions de forme se sont avérés être d'un grand intérêt. Les deux types d'opérations cognitives les plus représentatives, l'*association* et la *transformation*, ont été particulièrement reliées au processus de rappel de l'information en mémoire. Les résultats ont permis de décrire les mécanismes cognitifs qui comprennent l'encodage des informations, leur stockage dans la mémoire long-terme (MLT) et le passage des informations entre la mémoire de travail/et la mémoire court-terme (MT/MCT). De plus, nous avons pu confirmer une forte relation entre les opérations *attention visuo-spatiale* et *jugement/décision* (→ HYP 1.1); (2) en recueillant à la fois les expressions linguistiques et non linguistiques, nous avons partiellement quantifié les réactions émotionnelles des designers, qui peuvent entrer en jeu durant les processus cognitifs en générant les stimuli et aussi en évaluant les résultats durant des phases génératives. Nous allons par la suite améliorer la robustesse de ces résultats par les mesures physiologiques qui apportent des résultats objectifs (→ HYP 1.2). Les deux approches qualitative et quantitative ont été intégrées afin de produire un modèle cognitif riche du processus de catégorisation mentale de l'information qui sera présenté dans le chapitre V.

L'originalité des apports de recherche figure premièrement dans la quantification de l'information mentale et des opérations cognitives que les designers mettent en œuvre lors de la phase générative. Deuxièmement, elle réside dans l'approche de recherche-action et des expériences de laboratoire, qui nous a permis non seulement de construire un modèle des processus cognitif et affectif des designers, mais aussi de s'appuyer à la fois sur les approches théoriques et expérimentale afin d'appréhender les activités de conception amont qui sont spécifiques. Troisièmement, des théories et méthodes issues de la psycho-physiologie ont été intégrées dans le domaine des sciences de la conception.

4.2 EXP 2: Exploration de la réponse émotionnelle face aux représentations précoces (esquisses)

4.2.1 Objectifs

Le but de l'EXP 2 a été d'explorer la réponse émotionnelle vis-à-vis des premières représentations (les esquisses). Dans la phase générative, les designers commencent à se constituer des images mentales, après quoi les esquisses préliminaires constituent une première externalisation de ces images mentales (voir Figure 18). Les esquisses préliminaires, en tant que premières représentations, peuvent jouer un rôle important dans la transmission de l'intention du designer (sémantique et émotionnelle) et de la prédiction de la forme de produit fini.

L'EXP 2 a répondu à deux objectifs. Le premier était d'identifier la réponse émotionnelle vis-à-vis des représentations précoces, les esquisses. Le deuxième objectif était de quantifier cette réponse en combinant les méthodes cognitives avec les approches physiologiques.

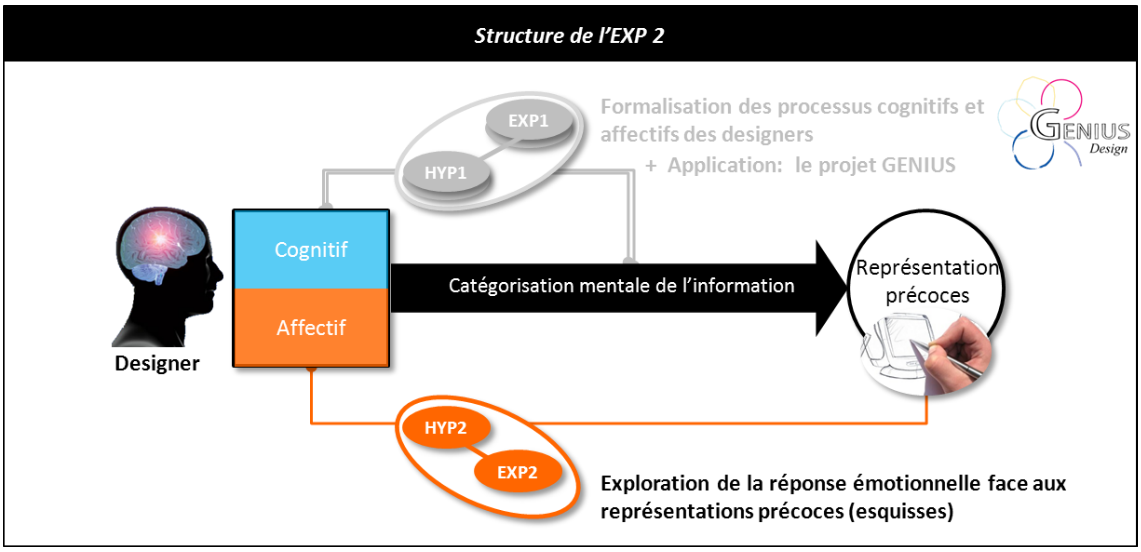


Figure 1058. Structure de l'EXP 2

4.2.2 Méthode

L'EXP 2 a été élaborée afin d'identifier et de quantifier la réponse émotionnelle vis-à-vis des esquisses préliminaires. Dans le domaine du design émotionnel et de l'ingénierie Kansei, les approches cognitives basées sur l'évaluation subjective ont été abondamment appliquées pour évaluer la réponse émotionnelle. Par exemple, un questionnaire basé sur l'utilisation des icônes de **Lang (1997)** et complété par une approche lexicale des émotions, en incluant une liste de 50 réactions émotionnelles proposées par le **Geneva Emotion Research Group (1988)** cependant a été élaboré dans **Mantelet (2006).**

Les méthodes cognitives ne peuvent pas fournir une réponse émotionnelle continue et objective. Ainsi, les études récentes dans le domaine de l'ingénierie Kansei tendent à coupler les méthodes cognitives avec les approches physiologiques basées sur la mesure de l'Activité électrodermale (l'EDA), la fréquence cardiaque et l'électroencéphalographie (l'EEG), etc. (**Tran et al., 2003; Ganglbauer et al., 2009).**

Par conséquent, pendant l'EXP 2, nous avons eu comme objectif de combiner les méthodes cognitives (web questionnaire) et physiologiques (l'activité électrodermale et eye-tracking), et d'identifier et de quantifier la réponse émotionnelle vis-à-vis des esquisses préliminaires. Toutes les mesures que nous avons pu extraire sont répertoriées Figure 19.

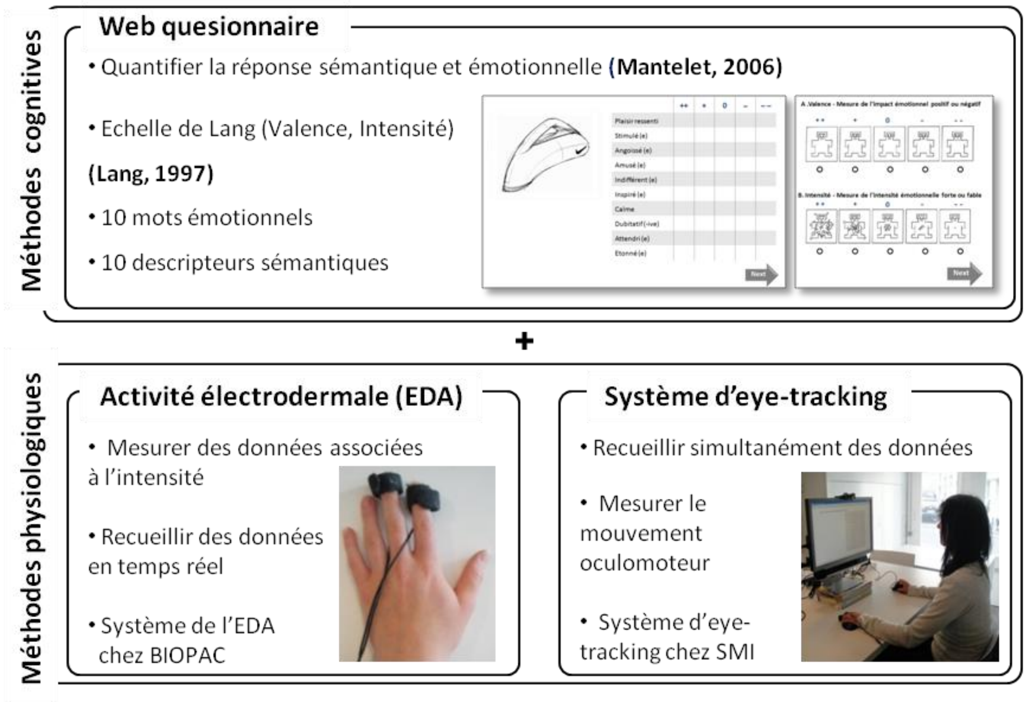


Figure 106. Bilan des approches cognitives et physiologiques

4.2.2.1 Participants

Pendant l'EXP 2, nous avons recruté 12 designers, répartis en six étudiants en master design produit (novices) et six expert designers produits (5/7 HF). Les six experts designers avaient en moyenne 9,2 années d'expérience.

4.2.2.2 Matériels et déroulement

Les questionnaires web ont consisté en trois types de transparents de présentation:

- Le **Transparent de Préparation** était une page blanche qui permet aux participants de stabiliser leur état émotionnel avant d'être soumis au transparent stimulus.
- Le **Transparent Stimulus** regroupait l'ensemble des images d'esquisses comme stimuli, issues d'un cahier des charges design sur l'*aspirateur Nike* (voir Figure 20)

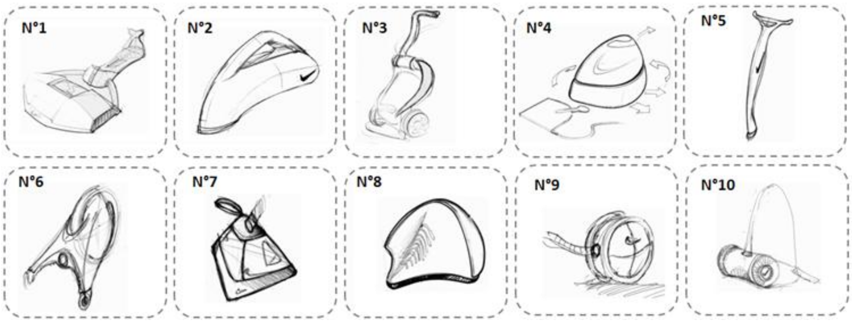


Figure 20. Dix esquisses sélectionnées en tant que stimuli visuels

- Le **Transparent pour l'évaluation** comportait trois types de questions décrites précédemment.
  - Les échelles de Lang (1997) : Self Assessment Manikin (SAM)
  - Une liste de 10 termes émotionnels à évaluer sur une échelle à 5 degrés : Amusé, stimulé, apeuré, enthousiasme, hésitant, mal à l'aise, passionné, surpris, impressionné
  - Une liste de 10 descripteurs sémantiques à évaluer sur une échelle à 5 degrés : Organique, sympatique, intelligent, léger, sportif, masculine, moderne, rapide, dynamique, rigide

Un système d'*eye-tracking* a permis d'enregistrer en même temps une capture vidéo de l'écran avec toutes les actions que les participants exécutent en procédant au remplissage du web questionnaire. Cette méthode permet d'enregistrer automatiquement la durée des actions pour que les données de l'activité électrodermale (EDA) puissent être synchronisées avec celles relatives au questionnaire. Selon la méthode de **Lang (1997)**, chaque test a débuté avec un transparent de préparation visualisé par les participants durant 5 secondes. Ensuite, un transparent *stimulus* a été présenté pendant 6 secondes. Finalement, les participants ont dû remplir le questionnaire intégré au transparent pour l'évaluation. A la fin de l'expérimentation, il a été demandé aux participants d'ordonner les trois esquisses pertinentes selon eux de 1 à 3 vis-à-vis du cahier des charges (l'aspirateur Nike), parmi les 10 esquisses (voir Figure 21).

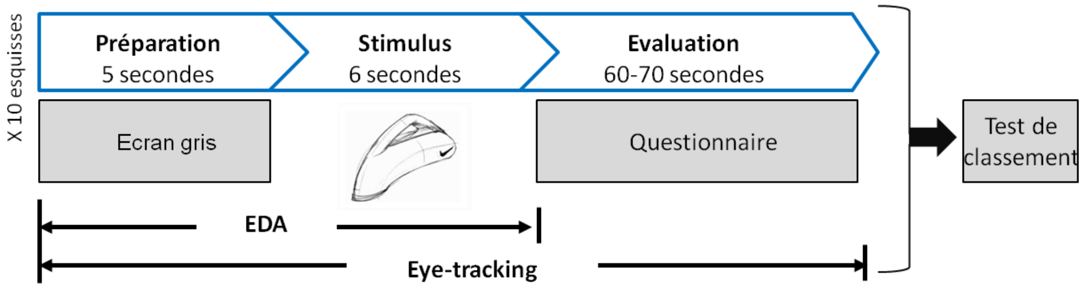


Figure 107. Procédure de l'EXP 2

Afin de valider la pertinence de la combinaison des mesures cognitives et physiologiques, nous avons conduit des tests pilotes avec des images d'animaux et de produits. Lors de ces tests nous avons pu confirmer qu'il y a une corrélation entre les résultats issus des approches cognitives et physiologiques.

4.2.2.3 Analyse des données

Les résultats issus des questionnaires ont été calculés par Analyse en Composantes Principales (ACP). Le but était d'explorer la manière dont les termes sémantiques et émotionnels sont utilisés afin d'établir les corrélations entre les réponses sémantiques et émotionnelles **(Mantelet, 2006; Bouchard et al., 2008; Nagamachi et al., 2009)**. Nous avons utilisé un programme spécifique pour cette analyse ''Statbox'' **(Grimmersoft, 2010**). D'autre part, les valeurs de l'activité électrodermale (EDA) les plus importantes ont été les changements correspondant au transparent de préparation et aux *transparents stimuli*. Donc, en premier lieu, nous avons d'abord segmenté les valeurs EDA pour 11 secondes chacune avec le logiciel ''Biopro 3.7'' **(BIOPAC, 2010)**. Ensuite, comme des différences inter-individuelles importantes étaient attendues, nous avons normalisé les valeurs EDA dans l'intervalle [0,1] en utilisant pour chacune la formule [Normalisée_EDA= (original_EDA /max_EDA]. Finalement, nous avons calculé la somme de chaque valeur EDA normalisée pour les 12 participants pendant 11 secondes, et en avons ensuite calculé la moyenne. A partir des informations recueillies par le biais du système d'*eye-tracking*, nous avons visualisé les traces de mouvements du regard sur des mappings prévus à cet effet, afin de mettre en évidence l'aire où se situe le focus grâce au logiciel ''Begaze™2'' **(SMI, 2010)**. Afin de redue plus robuste les résultats, nous avons souhaité mesurer d'autres critères physiologiques grâce au système *eye-tracking* telles que le nombre/durée, la taille des pupilles, et la vitesse de clignement/durée afin de compléter les signaux EDA. Les données ont été recueillies et vont faire l'objet d'analyse complémentaire en perspectives de cette thèse (→ §6.2).

4.2.3 Résultats et discussion

4.2.4.1 Corrélations relatives aux réponses sémantiques et émotionnelles

Afin d'identifier les réponses sémantiques et émotionnelles relatives aux esquisses préliminaires, une ACP a été appliquée. L'analyse a été complétée par un classement répondu de pertinence de ces esquisses vis-à-vis du cahier des charges. En plus, le classement de l'analyse a été utilisé pour renforcer les résultats issus de l'approche cognitive. La Figure 22 montre la position des dix descriptions sémantiques (diamants) et des dix esquisses (cercle en couleur) chacun dans la sphère des composants principaux extraite. Nous avons appliqué un code couleur pour chaque esquisses (cercle coloré) et un symbole sous forme d'étoile pour le classement, avec par exemple, classement 1 = 3 étoiles, classement 2 = 2 étoiles et classement 3 = 1 étoile, (voir Figure 22-23). La contribution cumulative de l'ACP montre des corrélations entre les descriptions sémantiques. Les deux facteurs (F1 et F2) expliquent 86,4% des résultats. Deux groupes sémantiques se dégagent, qui sont les suivants:

- Groupe sémantique 1 : moderne, rapide, dynamique, sportif, léger
- Groupe sémantique 2 : plaisant, organique

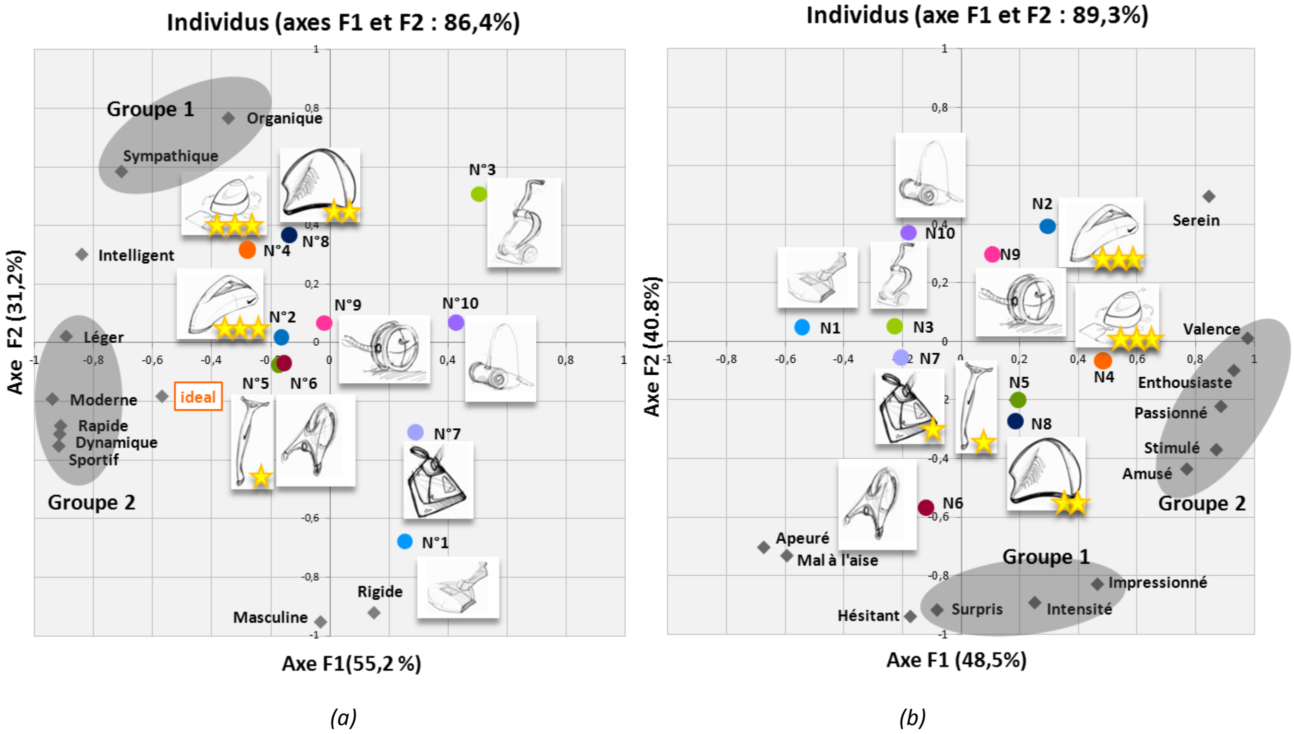


Figure 22. ACP des reposes sémantiques (a) et émotionnelles (b)

Les esquisses N2, N5 et N6 ont été plus représentatives du groupe sémantique 1, alors que les esquisses N4 et N8 ont été plus représentatives du groupe sémantique 2. Les deux groupes d’esquisses ont confirmés les résultats de l'analyse précédente concernant les réponses sémantiques. Nous avons supposé que les esquisses N2 et N4 notées en premier ont exprimé différentes réponses sémantiques. En effet ceux qui ont noté d’abord l’esquisse N2 n’ont pas sélectionné l’esquisse N4 en second et vice versa (à part un des 12 participants).

Selon l’ACP relative à l’analyse des réponses émotionnelles face aux esquisses (voir Figure 22b), les contributions de l’ACP décrite sur la sphère sont de 89,3% pour les deux facteurs F1 et F2. Les axes principaux ont été confirmés avec d’une part une valence positive—négative et d’autre part une intensité (excitation) haute—basse. La valence positive a fait apparaître des émotions complémentaires les unes des autres telles que : ‘‘*enthousiaste*’’, ‘‘*passionné*’’, ‘‘*stimulé*’’ et ‘‘*amusé*’’ *(Group émotionnelles 1)*. L’intensité la plus haute a été reliée aux émotions ‘‘*impressionné*” et ‘‘*surpris’ (Group émotionnelles 2)*. Nous avons constaté que trois premières esquisses classées (à part N2) sont reliées à droite ce qui correspond à une valence positive.

En synthèse, l’ACP des réponses sémantiques & émotionnelles et le classement ont permis d'identifier la réponse sémantique et émotionnelle face aux esquisses préliminaires en incluant tant les émotions primaires que secondaires. Il semble que les esquisses préliminaires soient capables d’exprimer des caractéristiques sémantiques fortes et de générer à la fois un sentiment positif et une réaction émotionnelle intense.

4.2.4.2 Corrélations relatives aux réponses émotionnelles entre l'approche cognitive et physiologique

La réponse émotionnelle provoquée par les esquisses préliminaires a été analysée à la fois par le biais d'une Analyse en Composantes Principale (ACP) (voir Figure 22b) et par une analyse des changements dans la réponse électrodermale (EDA) (Figure 23). Les capteurs EDA ont permis de mesurer en réponse la conductance de la peau (EDA) qui est généralement associée à l'intensité de l'émotion. La Figure 23 décrit la moyenne normalisée de la conductance de la peau pendant 11 secondes i.e., 5 secondes pour *le transparent de préparation* et 6 secondes pour le *transparent stimulus* comme cela est indiqué sur les lignes en pointillé. La partie la plus intéressante de cette figure se situe au niveau des pics et des creux relatif à la réponse électrodermale, qui a tendance à augmenter jusqu'à un pic pour la plupart des images stimuli.

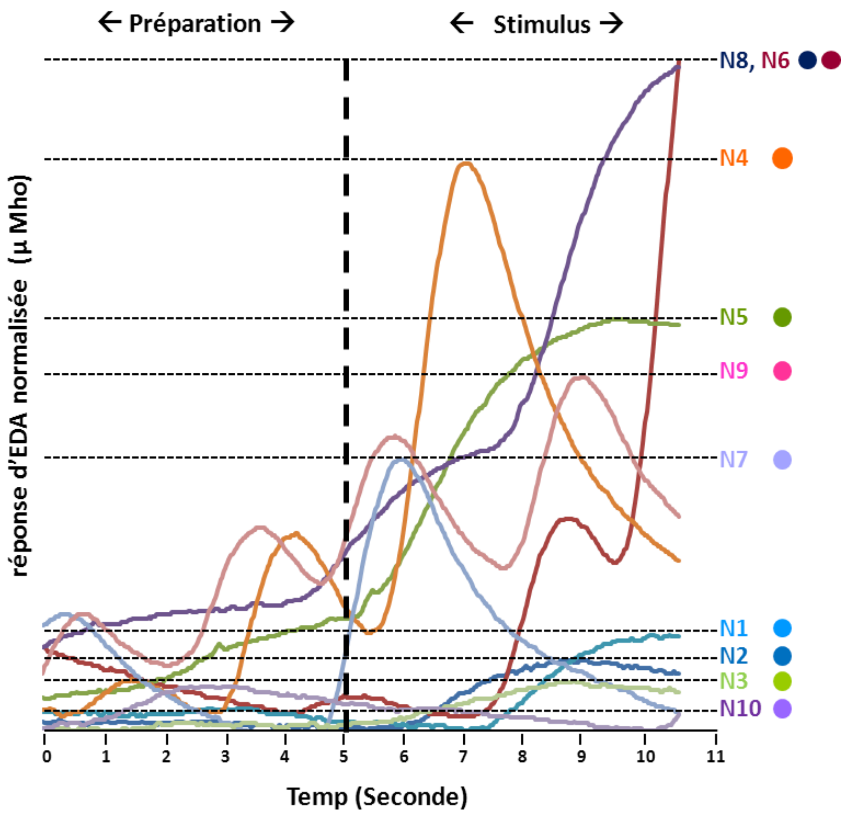


Figure 23. Changements dans la moyenne normalisée de l'EDA pendant les 11 premières secondes

Nous avons trouvé une corrélation positive entre les résultats de l'ACP et l'intensité mesurée à travers la conductance de la peau. Selon les Figures 22b et Figure 23, ces deux types de résultats montrent que les esquisses N8, N6 et N4 ont provoqué des réactions émotionnelles plus intenses, alors que les esquisses N1, N2, N3 et N10 ont provoqué des réactions émotionnelles plus faibles. Pour les autres esquisses, incluant les esquisses N5, N7 et N9, il a été plus difficile d'interpréter les corrélations.

4.2.3.5 Visualisation du mouvement oculomoteur

A l'aide du logiciel ''Begaze^{TM}2'' **(SMI, 2010)**, nous avons recueilli les traces de mouvements oculaires et le nombre des fixations. Ces traces ont pu être visualisées sous forme de mappings selon les techniques développées par **Spakov & Miniotas (2007)**. La Figure 24 montre que les participants regardent communément les esquisses préliminaires de manière discontinue. L'intensité relative de l'attention des participants représente une région intéressante et spécifique de l'image. Il s'avère que les designers ont fait particulièrement attention au logo Nike. Leur aire de fixation a été tout à fait convergente en termes de parties ou de lignes.

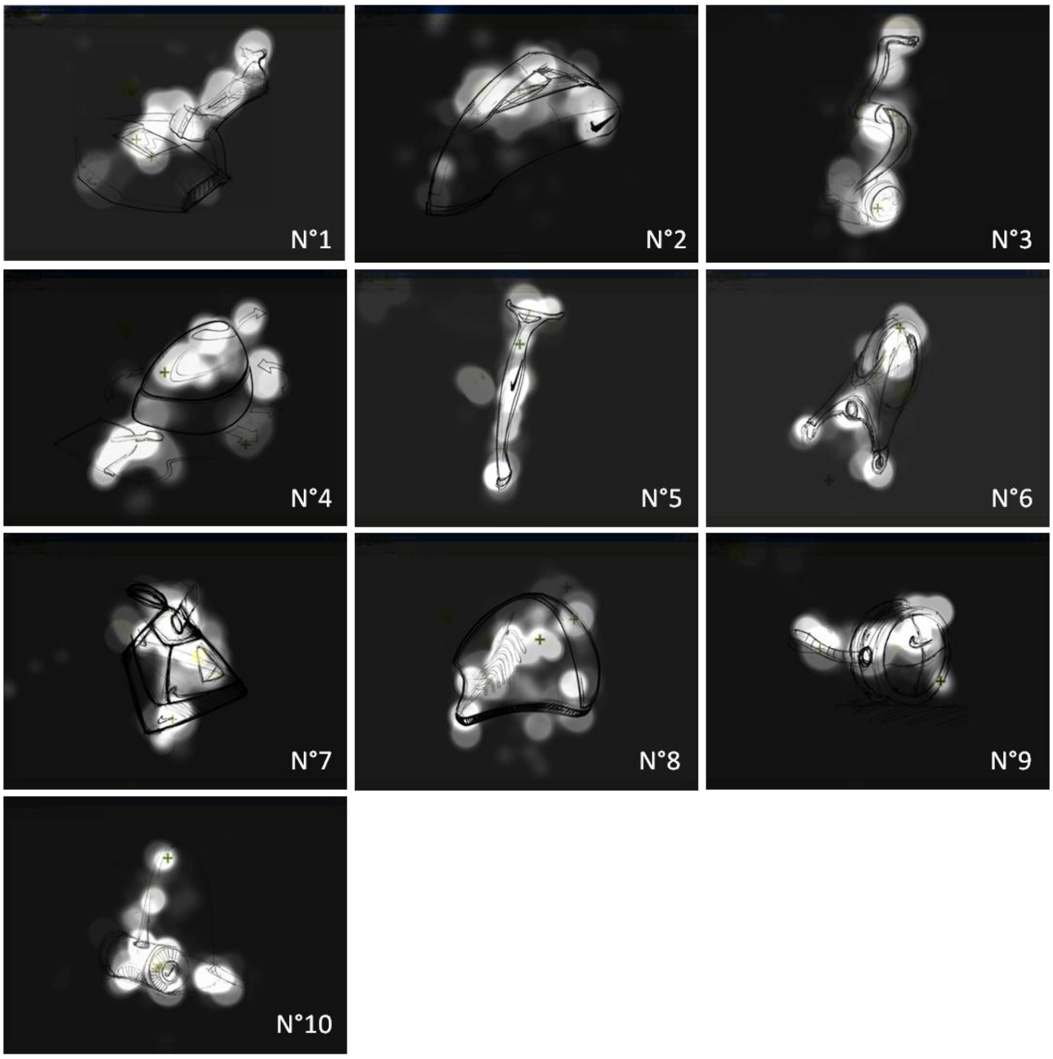


Figure 24. Mappings de résultats d'analyse du mouvement oculomoteur pour 12 designers

4.2.4 Conclusion et validation de l'HYP 2

Dans le cadre de l'EXP 2, nous avons souhaité identifier la réponse émotionnelle face aux représentations précoces telles que les esquisses. L'HYP 2 et les sous-hypothèses (HYP 2.1 et HYP 2.2) qui y sont relatives ont été validées durant l'EXP 2. L'HYP 2 concerne la formalisation de la réponse émotionnelle face aux esquisses préliminaires afin de pouvoir prédire la réponse émotionnelle vis-à-vis de concepts dès le stade des phases amont du design. Afin de répondre à cette hypothèse, nous avons proposé de coupler les méthodes cognitives et physiologiques. Les méthodes cognitives se basent sur le web questionnaire (valence/intensité selon la méthode SAM de Lang, descripteurs sémantiques et émotionnels et test de classement). Les approches physiologiques ont été basées sur l'analyse de l'activité électrodermale (EDA) et celle de l'activité et du mouvement oculomoteurs.

L'ACP des réponses sémantiques et émotionnelles ainsi que le classement nous ont permis d'identifier la réponse sémantique et émotionnelle face aux esquisses préliminaires en incluant à la fois les émotions primaires et secondaires. Nous avons conclu que les esquisses précoces sont capables d'exprimer des caractéristiques sémantiques fortes. De plus, ''la bonne forme'' peut provoquer un effet positif et un état émotionnel intense. →HYP 2.1.

Le couplage des résultats issus des méthodes cognitives et physiologiques a permis de quantifier la réponse émotionnelle vis-à-vis des esquisses préliminaires. La méthode cognitive a permis de spécifier des émotions secondaires obtenues avec les esquisses préliminaires, alors que la méthode physiologique a fourni des indications sur un état émotionnel continu en les quantifiant de manière objective.→HYP 2.2.

Nous avons couplé les méthodes cognitives et physiologiques afin de quantifier la réponse émotionnelle dans un contexte spécifique, celui de l'activité de designer. Etant donné que les esquisses préliminaires peuvent être moins enclines à provoquer des émotions que des représentations visuelles comportant des attributs multi-dimensionnels (forme, couleur, texture), l'avancée de recherche porte ici sur l'identification d'une réponse émotionnelle vis-à-vis des esquisses préliminaires à l'aide de résultats qualitatifs et quantitatifs appréhendée principalement à partir de la forme

V. MODÉLISATION DES PROCESSUS COGNITIFS ET AFFECTIFS DES DESIGNERS LORS DE LA PHASE GÉNÉRATIVE

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Sur la base d'une étude empirique mettant en œuvre une approche à la fois qualitative et quantitative, nous avons établi un modèle de processus cognitif et affectif relatif à l'activité de design. Il décrit le processus de catégorisation mentale de l'information lors de la phase générative. Ce modèle suggère une liste de spécifications pour développer des outils computationnels dédiés à la phase générative.

5.1 Modèle des processus cognitifs et affectifs des designers, lors du processus de catégorisation mentale de l'information en phase générative

La Figure 25 montre les processus cognitifs et affectifs des designers lors des deux cycles de catégorisation mentale de l'information et de génération d'esquisses. Ce modèle met en œuvre trois niveaux de mémorisation de l'information et montre les différentes opérations cognitives associées. Chaque cercle à droite représente les opérations cognitives qui entrent en jeu lors de la catégorisation mentale de l'information. Le cycle à gauche permettent d'élargir le modèle initial lié à la mémoire et montrent les représentations externes, ou la mémoire externe, grâce à laquelle les designers fixent des idées comme des témoins visuels pour une inspection ultérieure. En complément, dans la partie supérieure de la mémoire long-terme, le taux d'information mentale et l'intensité des liens entre ces informations sont représentés à la fois par la taille des carrés et celle des flèches bleutées. De plus, conjointement des processus cognitifs des designers, nous avons illustré comment leurs réactions émotionnelles peuvent permettre de contrôler cette phase spécifique en générant des stimuli tout en les évaluant (les flèches oranges).

Les cercles en pointillés montrent les opérations cognitives qui sont considérées comme essentielles afin de relier la mémoire long-terme aux mémoires dites de travail et court-terme, ne sont cependant pas lisibles à travers les modalités mises en œuvre naturellement par les designers. La taille des cercles indique la fréquence d'apparition de telle ou telle opération cognitive au sein du processus de catégorisation mentale, celle-ci ayant été révélée durant l'application de notre protocole d'observation.

Etant donné que notre expérimentation s'est centrée sur un processus descendant tiré plus par la mémoire que par des sources extérieures, les designers ont plus eu tendance à rappeler des informations mentales stockées dans leur mémoire. Le processus de rappel des informations en mémoire fait intervenir trois types d'opérations cognitives: le *questionnement*, l'*association* (ascendante, descendante ou équi-niveau) et la *transformation*. Comme l'indique la taille des flèches sur le schéma, avec un cahier des charges spécifique tel que celui utilisé dans notre expérimentations, les designers mettent surtout en œuvre l'opération d'*association* entre le même niveau d'information et plus spécifiquement de *fonction* à *fonction*, de *descripteurs sémantiques* à *descripteurs sémantiques*, ou de *fonctions* à *nom de secteur*. Ensuite, ils associent mentalement des informations en croisant différent niveaux d'abstraction de l'information tels que *fonction-forme, fonction-descripteurs sémantiques* et *descripteurs sémantiques-forme* et vice versa. C'est donc en particulier l'opération d'*association* qui a été prédominante lors de la production des esquisses. Les *transformations* quant à elles correspondent à des analogies réalisées à partir d'informations moyen-niveau (*fonctions*) et bas-niveau (*des descripteurs de forme*).

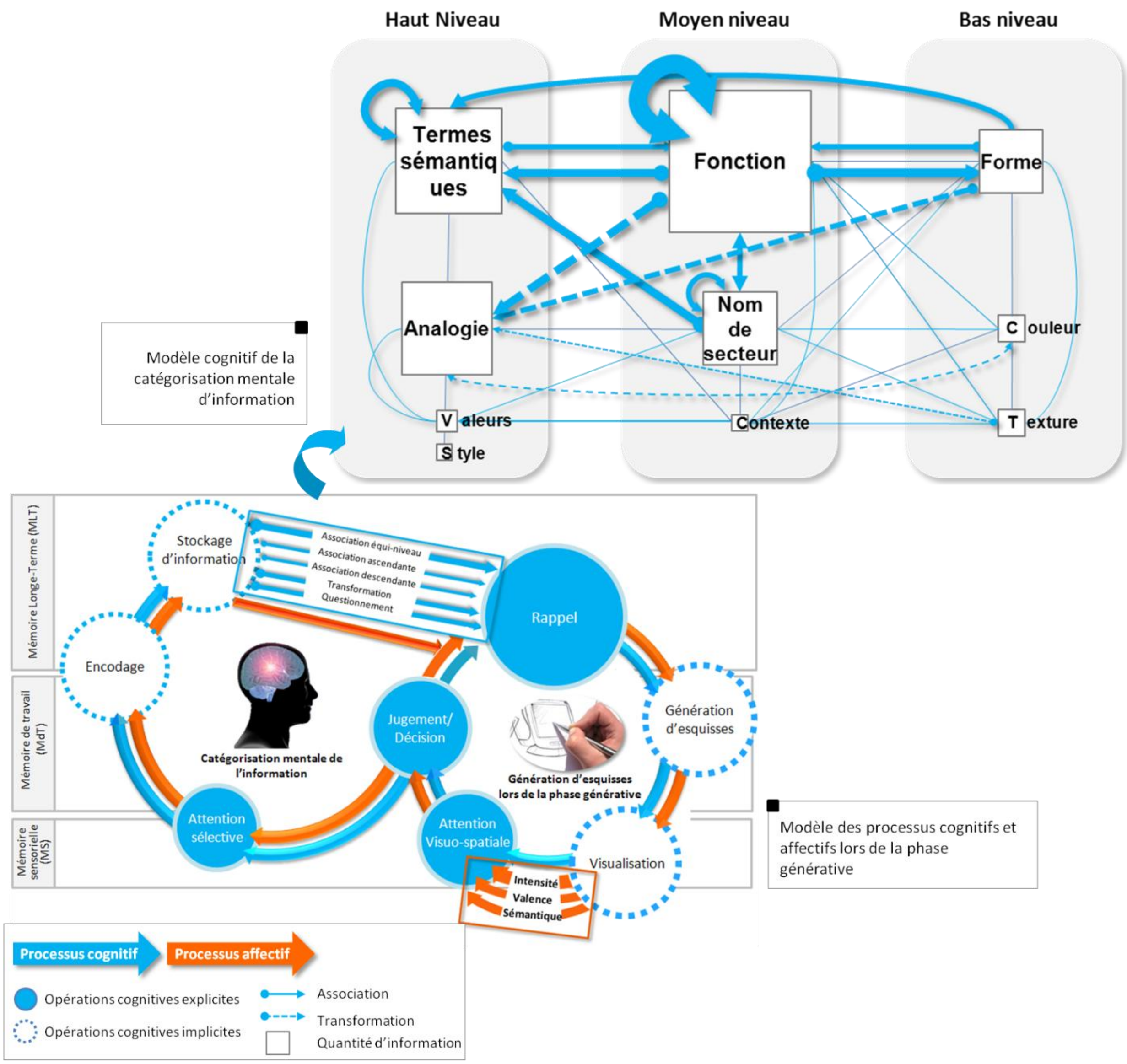


Figure 25. Modèle des processus cognitifs et affectifs lors de la phase générative

Pendant le processus de rappel, des images mentales partielles peuvent être externalisées lors de la production d'esquisses. Ces esquisses préliminaires ne sont cependant pas suffisamment matures pour être partagées avec d'autres acteurs. Elles sont plus là pour assister le processus de conceptualisation. Certaines parties de ces esquisses préliminaires activent l'*attention visuo-spatiale* des designers, ce qui les conduit à réaliser des *jugements*. Parmi les idées qui ont reçu un feed-back positif, s'il est nécessaire pour le designer de rappeler plus d'information afin de développer une idée, il arrive qu'il repasse sur une forme en se concentrant sur les parties à modifier. La fréquence d'apparition des opérations de questionnement est beaucoup plus rare et l'utilisation du *jugement* a été relativement basse en comparaison de l'opération d'association dans le cadre de notre analyse.

En complément des processus cognitifs, la recherche bibliographique précédente et nos expérimentations ont démontré que le mesure des réactions émotionnelles peut permettre de mieux appréhender la phase spécifique de génération et d'évaluation des représentations précoces. Par exemple, la « réponse affective » permet de réguler l'attention afin de s'adapter à la tâche en cours et de faciliter la prise en compte itérative des différents aspects des concepts et variantes de solutions. Elle peut aussi permettre d'activer l'information nécessaire à partir de la mémoire long-terme, à travers la dimension esthétique basée en partie sur des règles d'harmonie à la croisée des différents niveaux d'information. D'autre part, concernant l'impact émotionnel relatif à l'évaluation, les designers évaluent souvent les esquisses et les concepts vis à vis de ces règles et de la qualité hédonique des produits et de la satisfaction des designers.

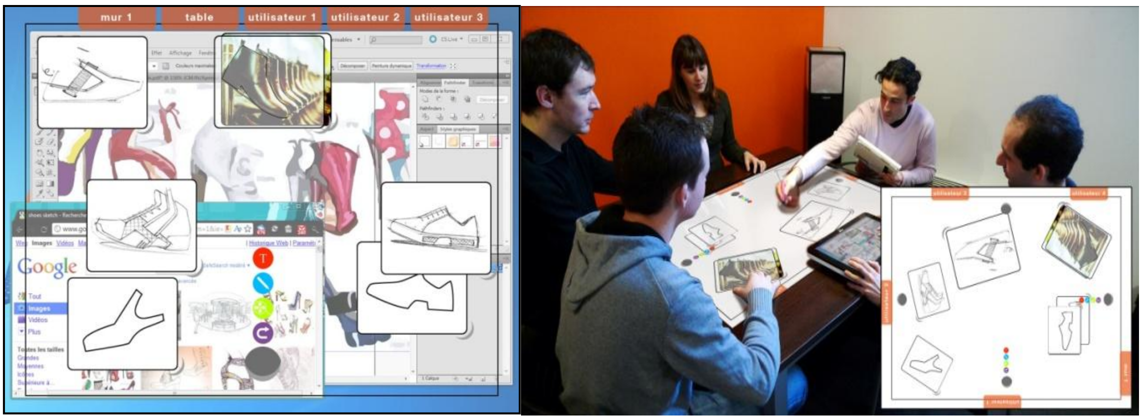
Même si le protocole basé sur les verbalisations s'est limité à quantifier les aspects émotionnels relatifs au processus du design, les résultats concernant l'expression vocale des émotions ont amené certains résultats. De plus, durant l'EXP 2, nous avons identifié une relation entre les aspects émotionnels du design et la génération précoce d'esquisses. Nous en avons conclu que les esquisses sont des représentations qui permettent d'exprimer la sémantique des concepts et provoquent déjà, à ce stade, des réactions émotionnelles. En particulier, la ''bonne forme'' des esquisses peut engendrer une valence positive et une intensité élevée. Les esquisses sont des premières représentations externes des représentations mentales, dont les aspects sémantiques et émotionnels reflètent déjà la valeur des solutions design. Les représentations précoces sous forme d'esquisses peuvent jouer un rôle pour véhiculer l'intention design et prédire les réponses des consommateurs.

5.2 Spécifications pour le développement d'outils computationnels dédiés à la phase générative

A partir des trois types de résultats obtenus, résultats qualitatifs, résultats quantitatifs et modèle de synthèse, nous avons exprimé un certain nombre de spécifications pour la conception et le développement d'un outil numérique dans le cadre du projet GENIUS (voir Tableau 4). En particulier, la validation d'un modèle cognitif et affectif a permis d'orienter et de caractériser plus précisément la définition fonctionnelle de l'outil GENIUS (voir Figure 26).

Tableau 4. Spécifications pour le développement d'outils computationnels dédiés à la phase générative

Catégories	*Spécifications détaillées*
Opérations cognitives d'association	• Le système doit permettre indépendamment d'aider dans la réalisation des liens entre les différents niveaux d'informations. L'intensité des liens devra être prise en compte. • Le système devrait aussi pouvoir permettre de rechercher une forme similaire d'un secteur à l'autre.
Opérations cognitives de transformation	• Le système doit de manière plus générale pouvoir aider dans tous types de transformations ou de réarrangements d'une forme. • Le système devrait offrir la possibilité d'effectuer des opérations graduelles de morphing de silhouettes entre des archétypes issus de différents secteurs.
Evaluation	• En termes de jugement esthétique, l'outil pourrait aider dans l'évaluation de l'adéquation à des règles esthétiques, où même proposer des évolutions dans ce sens, ou bien dans l'évaluation de l'adaptation de la forme à des descripteurs sémantiques en apportant un jugement objectif. • Il est aussi intéressant pour les designers de pouvoir maintenir une partie de forme d'objet fixe en faisant varier les parties restantes.
Navigation/ Visualisation	• L'outil doit être d'un apport important pour la visualisation (visualisation des mots, des liens entre les termes associés à des formes, des liens entre les mots et les formes,…). Il doit aussi permettre de comparer des formes. • Le système devrait permettre de visualiser une variation autour d'un archétype en fonction de descripteurs haut-niveau.



(a) *(b)*

Figure 1086(a) Interface GENIUS (prototype v.1), (b) Environnement de travail collaboratif (GENIUS D.7, 2009)

VI. CONCLUSION GÉNÉRALE ET PERSPECTIVES

Le chapitre VI se poursuit par une conclusion générale qui récapitule les principaux points clés de la thèse. Il se conclue par une discussion à propos des orientations de recherches futures. Celles-ci viseront à affiner les différents aspects du processus de design, aussi bien cognitifs, comportementaux, qu'affectifs; améliorer notre compréhension de la dimension émotionnelle à partir des représentations les plus précoces jusqu'aux produits finaux; et formaliser les phases précoces de la conception amont dans la perspective de développer de nouveaux outils computationnels.

6.1 Conclusion

Cette thèse s'est centrée sur 'les processus de catégorisation mentale de l'information' lors des phases génératives, au sein desquelles les designers emploient différents niveaux d'information mentale qu'ils intègrent et synthétisent peu à peu dans leur mémoire afin de générer ensuite les esquisses préliminaires. Conjointement des aspects cognitifs du design, nous avons proposé de modéliser les processus cognitifs et affectifs présents dans cette phase, à partir d'une compréhension des processus mentaux des designers et de leur relation avec des représentations précoces telles que les esquisses.

En appliquant à la fois une approche de recherche-action et des expériences de laboratoire, nous avons proposé initialement un modèle descriptif des processus informationnels qui s'appuie sur les théories de la mémoire issues de la psychologie cognitive. Afin d'enrichir et de valider ce modèle, nous avons conduit deux expérimentations avec des designers experts et novices dans le secteur du design produit. L'EXP 1 a porté sur les aspects cognitifs et affectifs du design durant l'étape de catégorisation mentale de l'information, alors que l'EXP 2 s'est focalisée sur la relation entre les aspects émotionnels chez les designers et sur les représentations associées dans cette phase spécifique. L'analyse qui a suivi nous a permis de définir un modèle des processus cognitifs et affectifs des designers, dédiés au processus de catégorisation mentale of information lors de la phase générative.

Ce modèle consiste en deux cycles que sont la catégorisation mentale de l'information et la génération précoce d'esquisses. Premièrement, le modèle de catégorisation mentale de l'information a porté plus particulièrement sur la structure de l'information design et sur les opérations cognitives. Ce modèle a ensuite été étendu à la phase de 'génération des esquisses préliminaires' afin d'expliciter les liens qui s'établissent entre la mémoire interne et la mémoire externe des designers via les 'représentations précoces'. De plus, conjointement des processus cognitifs des designers, nous avons illustré comment leurs réactions émotionnelles peuvent permettre de contrôler cette phase spécifique en générant des stimuli tout en les évaluant. En s'appuyant sur un projet de recherche qui a duré trois ans, le projet 'GENIUS', ce modèle nous a permis de définir des spécifications pour développer des outils computationnels dédiés aux phases génératives et de les implémenter au sein du système GENIUS.

L'originalité des apports de recherche de cette thèse porte sur les points suivants: (1) cette recherche a exploré un champ émergent de la recherche, ''les processus de catégorisation mentale de l'information inhérents à la phase générative''; (2) les processus cognitifs et affectifs des designers ont été étudiés conjointement; (3) une approche de recherche-action a été combinée avec des expérimentations de laboratoire afin de formaliser les activités spécifiques des designers; (4) la prédiction des émotions à partir des représentations précoces telles que les esquisses reste aussi un champ inexploré de la recherche en sciences de la conception, finalement (5) l'intégration de théories et méthodes issues de la psycho-physiologie en sciences de la conception nous a permis d'approfondir les résultats.

6.2 Perspectives

Les futures recherches dans le domaine devront investiguer les orientations suivantes (voir Figure 27):

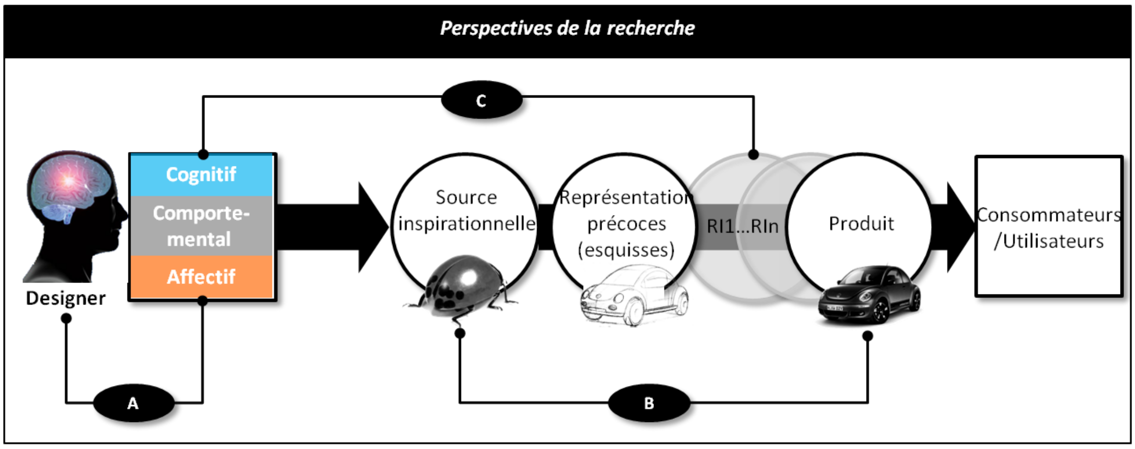


Figure 27. Perspectives de la recherche

A) Processus cognitifs, comportementaux et affectifs des designers

Selon **Norman et al. (2004)**, il existe trois niveaux de traitement de l'information: cognitif, comportemental et affectif. Nous nous intéressons particulièrement aux niveaux comportemental et affectif qui s'opèrent souvent inconsciemment. Concernant le niveau comportemental, il serait très intéressant de compléter la grille de codage par les dimensions posturales et gestuelles des designers. Concernant le niveau affectif, il est nécessaire d'explorer et de sélectionner les mesures physiologiques les plus appropriées, incluant l'électromyographie (EMG), l'électroencéphalographie, l'eye tracking, etc.

B) Prédiction des émotions en analysant les sources d'inspiration, les représentations précoces (les esquisses) et les produits finaux

Dans les phases amont du design, les designers emploient une large variété de sources inspirationnelles issues de différents champs: designs antérieurs, êtres vivants, éléments issus de la nature ou de notre vie courante **(Bouchard et al., 2008)**. Ainsi, nous nous intéressons tout d'abord au lien émotionnel entre les sources inspirationnelles, les représentations précoces telles que les esquisses, et les produits finaux ; cela devrait nous permettre de mieux comprendre comment les designers mettent en œuvre les aspects émotionnels des émotions dans leurs solutions design, et comment ces solutions sont perçues par les consommateurs durant le processus de conception dans sa totalité.

C) Outils computationnels dédiés aux phases amont du design

Dans cette thèse, comme champ d'application, nous avons présenté le système GENIUS, dédié à la phase générative. Sur la base de ce système, un travail complémentaire est nécessaire afin de développer des outils computationnels, qui pourraient couvrir les phases les plus précoces de la conception et améliorer la qualité des interfaces des produits. Finalement, ces outils computationnels vont ensuite aider les designers à générer des solutions design plus expressives, créatives, et plaisantes pour les consommateurs, en les assistant à la fois dans leur travail individuel et collectif.

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APPENDIX A:
CODING SCHEME OF
“COGNITIVE OPERATIONS”

(EN) Coding scheme of ''cognitive operations''

Coding (code)	Description	Examples (excerpts from the verbalizations)
Cognitive operations (Suwa & Tversky, 1997; Finke et al., 1992; Style, 2005)		
Selective attention	**Selectively attention through outer or inner senses (Style, 2005)**	
Ao	Selectively attention through outer senses (seeing, hearing, feeling, etc.)	*(In watching the bicycle wheel)' I had seen the mini- sports shoes on the bicycle wheel in the show window'*
Ai	Selectively attention through inner senses in a questioning way without containing new meaningful attributes	*What else is there ?*
Visuospatial attention	**Interpreting visual information, such as depict (Suwa & Tversky, 1997)**	
Pd	Attention to a visual feature of an element	*In profile, the screen should be this side for little more user-oriented, then a gripe on the right side.*
Pa	Attention to spatial or organizational relation between elements	*Maybe larger, rounder, like a little ball*
Questioning	**Questioning about ideas and emerging issues without answers or evaluations**	
Qh	Questioning about high-level information (values/semantic words/style)	*Does it feel sportive? It is a little static. I think that we want to something trendy.*
Qm	Questioning about middle-level information (sector name/function/context)	*Can I design a large module next to one person to reach the floor with his arm or just a small module?*
Ql	Questioning about low-level information (color/form/texture)	*The volume would be like this, 60-70% of the size comparing to a conventional vacuum cleaner. Why it would be smaller?*
Association	**Grouping ideas, finding similarity/uniformity, and difference/contrast (Descending/Ascending/Same level of association)**	
Descending association	**Association of design information in descending level**	
Ah2m	Association of *high level information* to *middle level information* (from semantic words/style/values to function/sector names/context)	*This is a traditional hand held type of vacuum cleaner. It should be linked to something fast with speed. For me, it joins the idea of Nike Air Max.*
Ah2l	Association of high level information to low level information (from semantic words/style/values to color/form/texture)	*If I start by an iPod which has a hard angles to differentiate into two components, fine plastic and bright/clean color, …*
Am2l	Association of middle level information to low level information (from function/sector names/context to color/form/texture)	*Do I design new accordion types of tube? or why not 'concentric' or 'linear' ones?*

Ascending association	**Association of design information in ascending level**	
Am2h	Association of m*iddle level information* to *high level information* (from function/sector names/context to semantic words/style/values)	*Imagine Nike sports bag, which is very organic and clean.*
Al2h	Association of low level information to high level information (from color/form/texture to semantic words/style/values)	*How about designing organic forms rather than concentric or linear ones?*
Al2m	Association of low level information to middle level information (from color/form/texture to function/sector names/context)	*Here is a transparent bag with a handle to take in dust.*
Same level of Association	**Association of design information at the same level**	
Ah2h	Association of high level information between semantic words/style/values	*How about other styles which are more organic and modern. We can get closer to American-style vacuum cleaner.*
Am2m	Association of middle level information between function/sector names/context	*Here, it should be connected to an electric plug, a tube, a bag …*
Al2l	Association of low level information between color/ texture	Transparent, double thickness, a little colorful…
Transformation	**Ideas are shifted/transformed to make interesting and useful entities such as new value and analogy (Finke et al., 1992)**	
Tl2h	Transformation low level information by analogy	*Nike makes me imagine a form like a Capricorns' horn which might be more rounded*
Tm2h	Transformation middle level information by analogy	*There is an automated vacuum cleaner, like a robot, which can move by itself.*
Judgment /Decision	**Make a judgment or evaluation on ideas according to the design brief, related to design information, or designer's satisfaction**	
Jl2h	Make a judgment or evaluation low level information by high level information	*Ah, this grip is too classic. This is not good.*
Jm2h	Make a judgment or evaluation middle level information by high level information	*I think that Nike is lack of its originality a little.*
Jl2m	Make a judgment or evaluation low level information by middle level information Justifying a proposed solution	*It is interesting to see that kind of shape, which fits into the movement of a wheel.*
Js	Make a judgment or evaluation by designer's satisfaction	*I like/dislike this form.*
Jd	Make decision or confirmer their idea without attaching new information	*Ok, I'll put this transparent tube here.*

(FR) Codage des opérations cognitives

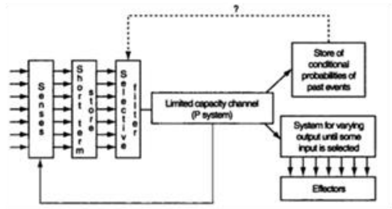
Catégorie	Description	**Exemples** (Extrait dans la verbalisation transcrite des designers)
Attention Sélective	**Se concentrer de manière sélective en sollicitant les sens externe ou interne (Styles, 2005)**	
Ao	Attention sélective selon sens externes	*En regardant un objet dans l'espace expérimental, j'ai vu cette forme*
Ai	Attention interne	*Qu'est-ce qui pourrait encore m'aider dans le choix de la forme ?*
Attention visuo-spatiale	**Attention visuo-spatiale des caractéristiques des éléments représentés sur l'esquisse (Suwa et al., 1998)**	
Pd	Attention visuo-spatiale entre des éléments de l'esquisse au sens 3D	*Vu de profil, il faut que mon écran il soit un petit peu orienté vers l'utilisateur, ensuite, une poignée vers ici*
Pa	Attention visuo-spatiale entre des éléments de l'esquisse au sens 2D	*Peut être plus grande plus arrondie, un peu plus boule finalement*
Questionnement	**Auto-questionnement à propos d'idées émergentes sans référer à un autre niveau d'information**	
Qh	Questions à propos d'idées émergentes liées à de l'information HN (descripteurs sémantiques, valeurs et styles)	*Est ce que ça fait sportif, c'est un peu statique, je pense que si on veut pouvoir dire que ça c'est un truc à la mode,*
Qm	Questions à propos d'idées émergentes liées à de l'information MN (secteurs, fonctions et contextes)	*Est ce qu'on ne pourrait pas sur une personne avoir d'un coté un grand module pour atteindre le sol avec le bras, et un petit module ?*
Ql	Questions à propos d'idées émergentes liées à de l'information BN (couleurs/formes/textures)	*Est ce que Pyramidale finalement c'est sympa?*
Association	**Association d'information descendant, ascendant, ou équi-niveau**	
Association descendante	**Association d'information descendante en conservant l'idée**	
Ah2m	Association descendante **HN→MN :** de descripteurs sémantiques/ styles/valeurs vers fonctions/secteurs /contextes	*On est sur une aspiration d'appoint donc quelque chose de rapide, avec la vitesse, pour moi tout ça rejoint l'ide de l'Air Max chez Nike,*
Ah2l	Association descendante **HN→BN :** de descripteurs sémantiques/ styles/ valeurs vers formes/ couleurs/textures	*Si on commençait comme un Ipod avec des angles durs pour différencier en bi-composants, des beaux plastiques, des couleurs claires propres,*
Am2l	Association descendante **MN→BN :** de fonctions/secteurs /contextes vers formes/couleurs/textures	*Est ce qu'on fait un nouveau 'type de tuyau accordéon', est ce qu'on le ferait pas 'concentrique' et 'linéaire'*

Association ascendante	**Association d’information ascendante en conservant l’idée**	
Am2h	Association ascendante **MN→HN :** de fonctions/secteurs /contextes vers descripteurs sémantiques/styles/valeurs	*Imaginons Nike, le sport Bac, un langage très organique très épuré,*
Al2h	Association ascendante **LN→HN :** de formes/couleurs/textures vers descripteurs sémantiques/ styles/valeurs	*Est ce qu'on le ferait pas concentrique et linéaire mais on le ferait avec une forme très organique,*
Al2m	Association ascendantes **BN→MN :** de formes/couleurs/textures vers fonctions/secteur /contexte	*Là c'est notre sac transparent le truc à poussière avec une poignée*
Association équi-niveau	**Association d’information équi-niveau en conservant l’idée**	
Ah2h	Association équi-niveau **HN↔HN** entre descripteurs sémantiques/ styles/ valeurs	*Et si c'était un autre style une forme très organique très moderne, et on va se rapprocher de l'aspirateur à l'américaine,*
Am2m	Association équi-niveau **MN↔MN** entre fonctions/secteur /contexte	*Et le tout en plus relié une prise électrique plus un tuyau pour le sac,*
Al2l	Association équi-niveau **BN↔BN** entre couleurs/textures	Transparent, tout le haut, double épaisseur, un peu de couleur
Transformation	**Transformer une idée origine par analogie (Finke et al, 1992)**	
Tl2h	Transformer une information **BN** par analogie	*Donc au lieu d'avoir l'accordéon classique qui est rectiligne on le fait avec une forme, de là on innove,*
Tm2h	Transformer une information **MN** par analogie	*Ah oui il y aussi l'aspirateur automatisé, l'espèce de robot qui se déplace tout seul,*
Jugement/ Décision	**Jugement orienté vers la décision et vers la solution en cours de définition**	
Jl2h	Jugement ou évaluation d’information BN avec information HN	*ah cette poignée est trop classique ce n’est pas bon ça!*
Jm2h	Jugement ou évaluation d’information MN avec information HN	*je pense que Nike déjà ils ont les moyens on peut être faire des trucs de, ça manque un peu d'originalité quand même,*
Jl2m	Jugement ou évaluation d’information BN avec information HN	*C’est intéressant de voir cette espèce de forme qui rentre dans l'autre là, un mouvement, imaginer que la roue*
Js	Jugement ou évaluation hédonique	*C'est plutôt sympa, / Ca me plait*
Jd	Prise de décision ou confirmation d’une idée	*Donc je mettrai bien un tube transparent là,*

APPENDIX B:
EXAMPLES OF HUMAN INFORMATION PROCESSING MODEL

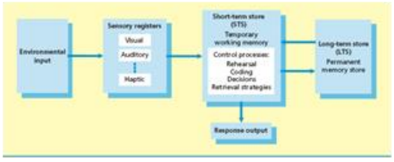
1. Broadbent (1958)

Model of human information processing



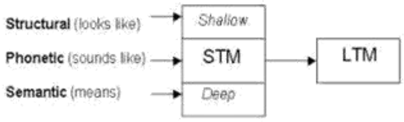
2. Atkinson & Shiffrin (1968)

Basic/Multi-Store Model of Memory



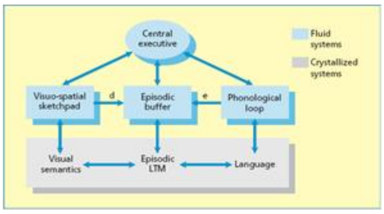
3. Craik & Lockhart (1972)

Level of processing



4. Baddely (1974,2000)

Multi component working memory model

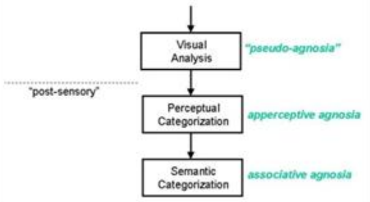


5. Lindsay & Norman (1977)

Information processing model

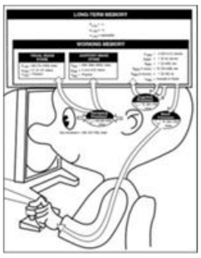
6. Warrington & Taylor (1978)

3-stage theory of object perception



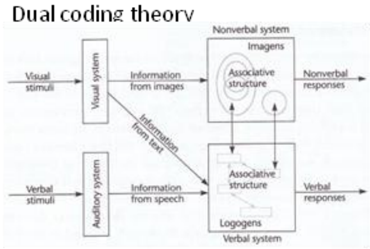
7. Card, Moran, and Newell (1980)

GOMS model



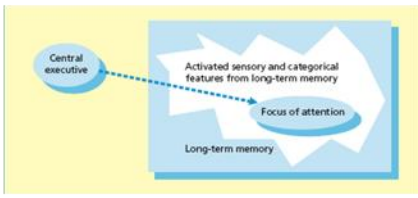
8. Paivio (1986)

Dual coding theory



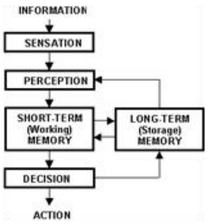
9. Cowan (1988)

Embedded-process model of working memory



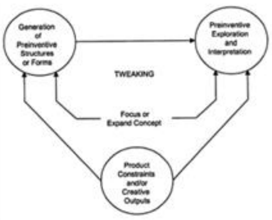
10. Harris (1992)

Components of human information processing



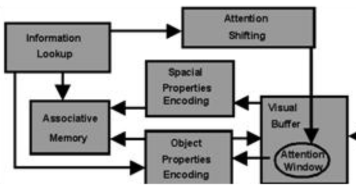
11. Fink, Ward & Smith (1992)

Greneplore Model



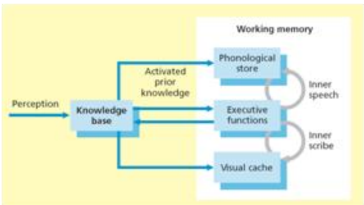
12. Kosslyn,S.M (1994)

Protomodel of visual object Identification



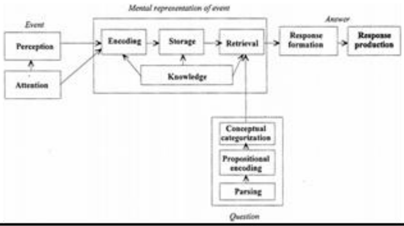
13. Logie & van der Meulen (1995)

Multicomponent working memory model



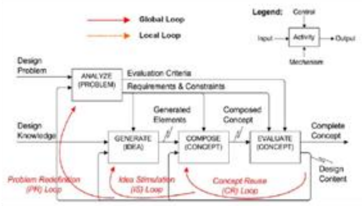
14. Ball & O'Callaghan (2001)

A Statement-Level Analysis



15. Jin & Chusilp (2006)

A cognitive activity model of conceptual design



APPENDIX C:
RESEARCH ACHIEVEMENTS

- **Designer's cognitive activities & computational tool for designers**

Bouchard C. **Kim J.E**., Omhover J.F., & Aoussat A. (2011) Cognitive Designers Activity Study, Formalization, Modelling, and Computation in the Inspirational Phase, CIRPDESIGN 2011, Daejeon, South Korea, Avril, 2010

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- **Kansei/Emotional design**

Kim J.E., Bouchard C. & Aoussat A. (2010) Emotional Impact on designer's cognitive process in the early stages of design, KEER2010 Conference

Bouchard C. **Kim J.E**., & Aoussat A (2009). Kansei Information Processing in Design, IASDR Conference, Seoul, South Korea, 18-22, October, 2009

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- **Designing graphical interface**

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JIEUN KIM

MODELISATION DES PROCESSUS COGNITIFS ET AFFECTIFS EN CONCEPTION AMONT:

APPLICATION AUX OPERATIONS DE CATEGORISATION MENTALE PRESENTES LORS DES PHASES GENERATIVES

RESUME : Cette thèse a pour finalité l'analyse de l'activité cognitive des designers en vue de formaliser les processus informationnels inhérents aux activités de design industriel et plus particulièrement les activités de catégorisation mentale de l'information implicite qui précède la génération d'esquisses. Un tel modèle formalisé est nécessaire pour, à partir d'une extraction de la connaissance et des règles de design, élaborer de nouveaux outils numériques qui supporteront les processus informationnels amont en conception innovante. Nous avons mis en place deux expérimentations avec des designers experts et novices, afin de mieux décrire les processus cognitifs et affectifs des designers. Nous avons combiné la méthode cognitive (Protocole d'étude selon la méthode de verbalisation spontanée, questionnaire) et physiologique (Activité Electrodermale et eye tracking). La démarche a bénéficié comme terrain expérimental du projet national GENIUS. Ce projet visait à développer un système support à l'activité des designers dans la phase de catégorisation et de génération en conception amont. Notre apport s'appuie sur la formalisation d'un modèle des processus cognitif et affectif des designers. Ce modèle a permis d'extraire des spécifications pour le développement du système ‘‘GENIUS''.

Mots clés : design, catégorisation mentale, génération d'esquisses, processus cognitif et affectif, méthodes cognitives et physiologiques, représentation intermédiaire, outil numérique d'aide à la conception,

MODELING COGNITIVE AND AFFECTIVE PROCESSES OF DESIGNERS IN THE EARLY STAGES OF DESIGN:

MENTAL CATEGORIZATION OF INFORMATION PROCESSING

ABSTRACT : The aim of this thesis is to explore how designers mentally categorize design information during early sketching performed in the generative phase. In conjunction with cognitive aspects of design, we proposed that cognitive and affective processes, involved in this specific phase, should be modeled through understanding designer's mental process and its relationship with early representations (sketches) together. A combination of action research approach and laboratory-based experiments was particularly appropriate for our study. Thus, first, a descriptive model of information processing involving memory theories drawn from cognitive psychology was developed. This model was refined and enriched via empirical studies with experts and novices in the product design domain. In order to formalize cognitive and affective processes of designers, we combined cognitive (concurrent verbalization protocol and questionnaires) and physiological (galvanic skin conductance and eye tracking system) methods. Subsequent analysis finally yielded a model depicting cognitive and affective processes of designers in the generative phase. As an application, based on our model, a list of specifications for developing computational tools dedicated to the generative phase has been applied and validated in the ‘‘GENIUS'' project, which aimed to develop the system for supporting designer's activities in the early stages of design.

Keywords : design, mental categorization, sketching, cognitive and affective processes, cognitive and physiological methods, early representations, computational tools