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DESIGN COGNITION FOR CONCEPTUAL DESIGN

Doctoral Dissertation

Lassi A. Liikkanen

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Faculty of Engineering and Architecture
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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Engineering and Architecture for public examination and debate in The Stage of Design Factory at the Aalto University School of Science and Technology (Espoo, Finland) on the 19th of February, 2010, at 12 noon.

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School of Science and Technology
Faculty of Engineering and Architecture
Department of Engineering Design and Production

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Field of research	Early product development, cognitive design theory
Pre-examiners	Bernard A. Nijstad, Jami J. Shah
Opponent(s)	Henri H.C.M. Christiaans
Supervisor	Kalevi Ekman
Instructor	Kalevi Ekman

Abstract

Creative competences are the major currency in 21st century product development domain. Consequentially, the number of new methodologies and working styles targeted for the fuzzy front-end constantly increases. In response, those responsible for managing the early phases of product design need to repeatedly question methods, the organization of work, and the constitution of a design team. In this dissertation I argue that the development of design practices can benefit from a science of design that can provide robust evidence about successful and purposeful ways of working. I particularly endorse a psychological science of design which concerns mental constructs that underlie design work regardless of the utilized tools and methods.

This dissertation is motivated by an urge to understand the generation of ideas in conceptual design. By idea generation, I refer to the rapid production of seeds for future products or services, not necessarily very clever or unique yet. The goal is to develop a psychologically plausible view on how this kind of idea generation unfolds and particularly how human memory processes underlie this activity. This kind of cognitive, descriptive account is considered necessary to highlight the reality of design work in contrast to the prevalent prescriptive models of design.

This thesis reviews the existing literature on design idea generation and general theories of idea generation. Based on several empirical studies and cycles of theoretical development, I develop a heuristic model of conceptual design; an example of design cognition for conceptual design. The model is utilized as an explanatory framework to argue why certain phenomena (e.g. incubation, inspiration, and fixation) arise and influence design idea generation as they do. The model emphasizes memory search, recognition, and analogical transfer as essential cognitive processes in idea generation.

As a critical reflection of the work, I come to acknowledge the need to expand the cognitive theory beyond its present scope. I see that the design cognition needs to give up the problem solving perspective and consider new discourses to keep up with the accounts based on social constructivism. In future, I believe that establishing a science of design should help both educators and practitioners to advance their skills and help developing more effective and designer-centered practices.

Keywords	design cognition, conceptual design, idea generation, creativity, cognitive modeling		
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Tutkimusala	Varhaisen vaiheen tuotesuunnittelu, kognitiivinen suunnitteluteoria
Esitarkastajat	Bernard A. Nijstad, Jami J. Shah
Vastaväittäjä(t)	Henri H.C.M. Christiaans
Työn valvoja	Kalevi Ekman
Työn ohjaaja	Kalevi Ekman

Tiivistelmä

Luovuudesta on muodostunut yksi 2000-luvun tuotekehityksen taikasanoista. Uusien työskentelytapojen ja suunnittelumenetelmien lisääntyessä suunnittelutyön esimiesten on jatkuvasti tarkistettava vanhoja käsityksiään käytössä olevista menetelmistä, työn organisoinnista ja suunnittelutiimien kokoonpanosta. Tässä työssä esitän, että tämänkaltainen päätöksenteko tarvitsee onnistuakseen tieteellistä pohjaa. Suunnittelutyön ohjaamista koskevissa päätöksissä suunnittelututkimus voi tarjota hyödyllistä tietoa tuotekehityksen alkuvaiheeseen. Psykologinen suunnitteluntutkimus vaikuttaa tässä suhteessa lupaavalle. Se tarjoaa tukevan perustan, jolle menetelmien ja työkalujen käyttö pohjautuu.

Tämän tutkielman tavoitteena on tutkia konseptisuunnitteluun liittyvää ideointia psykologisesta näkökulmasta. Ideoinnilla tässä työssä tarkoitetaan nopeaa alustavien tuote- tai palvelukonseptien kehittelyä. Konseptisuunnittelussa uudet ideat ovat välttämättömiä, vaikka niiden alkumuodot eivät vaikuttaisikaan erityisen mullistavilta tai uniikeilta. Väitöskirjan tavoitteena on esittää psykologisesti uskottava malli siitä, miten erilaiset kognitiiviset mekanismit mahdollistavat ideoinnin. Tällainen kuvaileva malli ideoinnista on tarpeen suunnittelun luonteen ja dynamiikan ymmärtämiseksi, sillä suunnittelussa yleisesti hyödynnettävät preskriptiiviset mallit eivät tähän pysty.

Tutkielma sisältää tiivistelmän ideointia suunnittelussa koskevasta kirjallisuudesta sekä useiden kokeellisten tutkimusten tuloksista. Työn keskeisenä tuloksena esitän heuristisen mallin konseptisuunnittelusta kognitiivisena toimintana. Väitöskirjassa mallia hyödynnetään selittämään sitä, miksi erilaisia empiirisessä tutkimuksessa havaittuja ideoinnin ilmiöitä (fiksaatio, inspiraatio, inkubaatio) esiintyy ja mihin niiden vaikutus perustuu. Keskeisinä selitysmekanismeina työssä esitetään muistista hakua, tunnistamista ja analogista päättelyä.

Tutkielman pohdinnassa väitän, ettei kognitiivisen suunnittelun teoria nykytilassaan ole riittävän laaja kuvaamaan konseptisuunnittelua. Tulevaisuudessa suunnittelukognitioksi kutsuttavan lähestymistavan täytyy irrottautua ongelmanratkaisuun perustuvasta näkökulmasta ja ottaa vastaan uusia ajattelutapoja, jos se haluaa kyetä haastamaan tällä hetkellä vallitsevat, sosiaaliseen konstruktivismiin perustuvat teoriat. Uskon, että uudistuva suunnittelukognition teoria pystyy tulevaisuudessa luomaan suunnittelua koskevaa tietoa, joka auttaa kouluttajia ja suunnittelijoita kehittämään parempia suunnittelukäytäntöjä.

Asiasanat konseptisuunnittelu, ideointi, suunnittelupsykologia, kognitiivinen mallintaminen, luovuus

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Preface

The background for this thesis was laid out in 2005. At the time I started preparing my Master's thesis at the **Helsinki University of Technology** and work with researcher **Matti Perttula**. This thesis for the degree of Master of Arts at University of Helsinki was completed later the same year. My stay with the product development research group lasted until early 2006 and produced the first three publication included in this thesis. After this I ventured to the University of Helsinki to work on cognitive brain research and the remaining publications of this thesis were prepared sporadically. Until 2008, I never thought that this dissertation would be written.

However, things evolved so that I started preparing this thesis in early 2009. A personal grant from **Wihuri foundation** (Antti ja Jenni Wihurin säätiö) made it possible for me to get involved in the writing. This grant is greatly acknowledged as the completion of this thesis would have been impossible without it. I am also thankful for the flexibility of my present organization, **Helsinki Institute for Information Technology HIIT** (joint venture of Helsinki University of Technology TKK and University of Helsinki) and its former co-director Professor **Martti Mäntylä** and his successor Professor **Heikki Mannila** who allowed me to divide my time between ongoing research projects and thesis writing.

As this work was being written from January to June 2009, I worked for a **Tekes** funded **Theseus** project, which also facilitated the production of this thesis. The collaboration with Theseus researcher community at Jyväskylä University and VTT Tampere facilitated my work and opened up new perspectives for it. In particular, I thank Adjunct Professor **Antti Oulasvirta** (HIIT) and Professor **Pertti Saariluoma** (University of Jyväskylä) for their guidance and encouragement in the process. Since December 2008 I refreshed contacts to the local product design community. Aalto University pilot Design factory lead by Professor **Kalevi Ekman** allowed me kindly to work in their new premises and meet people interested in design thinking, innovation management, and industrial creativity. Prof. Ekman has also supervised this dissertation. Finally, I acknowledge the peer-support from the researcher **Salu Ylirisku** working at the Industrial design department of Helsinki University of Art Design (TAIK) for several enlightening discussions about the nature conceptual design during the spring. I look forward reading his dissertation in the near future.

There were many people involved in the preparation of the original publications and in the development of design theory within. I initially worked in the Navigo research project at the Helsinki University of Technology, funded by the **Academy of Finland.** The empirical investigations were carried out in close collaboration with Matti Perttula, who later claimed his doctorate. Designer **Pekka Sipilä** and prof. Ekman had also an important role in Navigo.

Although the majority of empirical work was carried out in 2005, I kept on with the analyses and distillation of data for a couple of years.

As my affiliation with Navigo came to an end in early 2006, I maintained connections to a few other design researchers. In particular, MSc **Sauli Honkala** helped during the preparation of the manuscript that was later accepted into Journal of Engineering Design. That paper built on previous work with Perttula, but needed a fresh theoretical perspective. University of Helsinki and the Department of Psychology at the time kindly provided help in the form of infrastructure during the writing processes. Especially I acknowledge the long-term support from Professor **Heikki Summala** and the Traffic research unit. I am also thankful for the brief period spent in Cognitive Science unit in 2007, where I worked with PhD **Pauli Brattico** and researcher **Alina Leminen**.

In 2007 I started working at the HIIT and developed new interests to idea generation and conceptual design, partially due to the influence of Professor **Lars-Erik Holmquist**. Consequentially, I desired to make a stance on a highly practical issue, time management, before kicking off the dissertation project and so I analyzed the literature on time constraints in January 2009. I transformed this analysis into a manuscript and with the helpful comments from **Tua Björklund**, **Matti M. Hämäläinen**, and **Mikko Koskinen,** all working in and around Design Factory. The last step in the process was the revision of the dissertation manuscript which prepared during the time I was enjoying doctoral student funding from the **Faculty of Engineering and Architecture** at TKK. During this time, I also studied under the supervision of Professor **Matti Vartiainen** (TKK) topics related to psychology of organizations and innovation. The final and likely the biggest impact to of this work was made both examiners of the thesis. I am very grateful for receiving comments to my manuscript from Professor **Bernard A. Nijstad** and Professor **Jami J. Shah.** I consider both of the most acknowledgeable people to comment this work and their participation was highly appreciated and valuable.

Having now walked you through the history of this dissertation, the list of acknowledgements was already quite long. However, above all I must express my gratitude to my closest family, especially **Riikka**, for the support during the years of exploration in the rough waters of scientific research and publication.

Thank you all!

December 2009, in Helsinki, Finland

Lassi A. Liikkanen

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List of Publications

This thesis is based on the following publications which are referred to in the dissertation by their Roman numerals:

I Liikkanen, L. A. & Perttula, M. (2009). Exploring problem decomposition among novice designers. *Design Studies*, 30(1), 38-59.

II Liikkanen, L. A. & Perttula, M. (in press). Inspiring design idea generation: Insights from a memory-search perspective. *Journal of Engineering Design*. Electronic version available: http://dx.doi.org/10.1080/09544820802353297

III Liikkanen, L. A. & Perttula, M. (2006). Contextual cueing and verbal stimuli in design idea generation. In J. S. Gero (Ed.), *Design Computing and Cognition '06* (pp. 619-631). Eindhoven, Netherlands: Springer Verlag.

IV Liikkanen, L. A., Björklund T., Koskinen M. & Hämäläinen M. (2009). Time Constraints in Design Idea Generation. In the proceedings of the *International Conference on Engineering Design, ICED 2009*, Palo Alto, CA.

V Liikkanen, L. A., Perttula, M. & Sipilä, P. (2008). Design Students' Preferences and Conceptions of Idea Generation in Groups. In the proceedings of the *NordDesign 2008*, Tallinn, Estonia.

VI Perttula, M. & Liikkanen, L. A. (2006). Structural tendencies and exposure effects in design idea generation. In the proceedings of *ASME 2006 International Design Engineering Technical Conference*, Philadelphia, Pennsylvania, USA.

VII Perttula, M. & Liikkanen, L. A. (2005). Cue-based memory probing in design idea generation. In the proceedings of the *Sixth International Roundtable Conference on Computational and Cognitive Models of Creative Design*, Queensland, Australia.

Author's Contribution in the Publications

The foundations of the empirical studies (**I-III, V-VI**) were laid out when the author was involved in the Navigo research project at the Product Development Research unit in Helsinki University of Technology. During 2005-2006, he closely collaborated with Matti Perttula and Pekka Sipilä, and jointly planned and executed several experimental studies of conceptual design. Some of those studies where documented together with Perttula (**III, IV, VI**) and for those studies the analysis and writing was done collaboratively. The theoretical paper **VII** was also prepared collaboratively with Perttula. The division of the contributions for each article is indicated in the tabulation at the bottom of this page.

After departing from the Navigo project, the author continued reporting and analyzing the findings from the research carried out previously and developing new insight about design theory independently. Publications **I** and **II** have been written solely by the author based on the experiments designed and implemented with Perttula inspired by his doctoral thesis. The publication **V** includes some written contributions from Perttula and is based on a design created together with Sipilä and Perttula, but was written primarily by the author. The paper **IV** was created when the author joined the Design Factory community with the help of comments from Tua Björklund, Matti M. Hämäläinen, and Mikko Koskinen.

Contribution in each publication is indicated by terms *major, equal, minor,* or not applicable (-).

Publication	*Writing*	*Theory & Design*	*Empirical work*	*Data analysis*
I	Major	Major	Equal	Major
II	Major	Major	Equal	Major
III	Equal	Equal	Equal	Major
IV	Major	Major	-	Major
V	Major	Major	Equal	Major
VI	Minor	Equal	Minor	Minor
VII	Equal	Equal	-	-

List of Abbreviations

CAD	computer-aided design
CNMC	cognitive network model of creativity
DUX	design for user experience
EM	external memory
HCI	human-computer interaction
IG	idea generation
LTM	long-term memory
PD	product development
R&D	research and development
SIAM	search for ideas in associate memory
VHIM	Vargas Hernandez ideation model
UCD	user-centered design
UID	user-inspired design
VDI	verein deutscher ingenieure
WM	working memory
WMC	working-memory capacity

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1 Introduction

At the end of the first decade of the third millennium, design research is in a state bewilderment. The past decades have introduced a number of movements in design methodology and research. Similarly design thinking and theorizing have transformed to several directions which have very little to do with each other. No leading theory and methodology has emerged, and according to industrial design theorist Krippendorff (2006), the old ones have faded and what remains is a strange mixture of multiple old fashions. One consequence of this is the tragedy that design research currently produces very little accumulative knowledge (Norman, 2009). However, even if there is and has been confusion among design researchers and theorists, there is no denying that many excellent products have been designed during the past 30 years.

This confusion of design research stems from multiple sources. Decades ago design researchers thought they had been able to define what design is, how it should be characterized, and what methods best suite design practice. Some years later many methodologists had to revise their beliefs (Cross, 1984) and became skeptical of design science. It is also evident that the requirements for designers' practical work have radically changed in few decades. Be it industrial or mechanical design, the complexity of designed artifacts has evolved from designing individual products, nuts and bolts, into designing meaning, interaction, brands, projects, and even discourses (Krippendorff, 2006; see Figure 1.1 below).

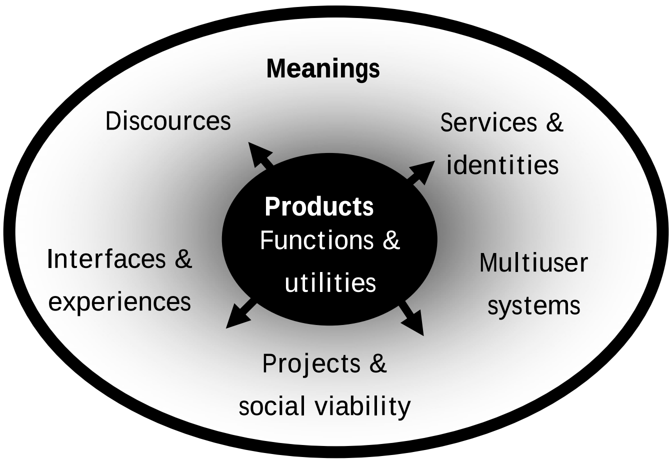

Figure 1.1 The expansion of designer's responsibilities from defining products to designing semantics (meanings) based on Krippendorff (2006).

Despite difficulties in establishing firm design tools, the cult of the method men has not died out. Even if design theorists have not taken in any new methodological beliefs, it seems that the concrete achievements of design may nourish the idea design is plain work and thus any skilled and experienced practitioner may feel free to present their beliefs and methods about design. Of course it is perfectly legal and even recommended to disseminate the proceedings of good design practices into the world. However, these best practices, maybe grounded in compelling and glorious experiences, can be fitting to their own setting, but can we trust to follow them blindly? Do they provide enough evidence about their qualities? In this thesis I defend the perspective that a theoretical understanding of design, a science of design, can facilitate the evaluation and the development of design methodology, and can therefore ultimately lead to better products.

The research question I consider in this work is *what sort of mental information processes are required to produce simple ideas in the early phases of design.* As an answer, I will provide a cognitive theory of design work, built upon the symbolic, problem-solving view of design. This theory is developed from a series of theoretical and empirical exploration into the nature of idea generation (IG) in design, but also considering other creative domains. The aim is to provide insights about the structure of design IG as creative work and investigate how it might be best supported. I do not claim to close the distances between practice, methods, and theory as I will also point out the inherent difficulties in the application of this theory and acknowledge the limited scope of the present approach. The notion of creativity in this thesis must also be understood as simple, everyday generativity, or personal creativity rather than revolutionary, cultural, or historical creativity commonly equated with the term (Boden, 2004).

In this first chapter, I start by reviewing the state of design and research, analyzing the existing design thinking approaches, introducing concepts relevant for design cognition, and outlining the work. In the second chapter, I review selected literature about empirical research on design, theoretical models of design IG, and the prominent empirical findings so far. The third chapter presents thesis' main argument which is a synthesis of the previous work. This cognitive theory of design IG process is presented as a heuristic, algorithmic cognitive model. The model combines elements from the publications and presents a conceptualization of how new ideas can be created in the early phases of the design process. In the final chapter I conclude this work by evaluating my contribution to the design cognition community along with its limitations. I also propose some open questions that should be studied in the future, and consider whether a change of paradigm in design thinking is desired or already happening. Together these chapters aim to provide a rich description about what IG in product design currently is, and what it may turn into in the future.

1.1 Design and Studies

What is design and how can it be investigated? Design surrounds us in a western society where our daily life revolves around a composition of artifacts. In the 21st century, it is not uncommon that people already live their lives and construct their identities inside one of the greatest artifacts, the Internet. Therefore, design might be labeled as the science of the artificial (Simon, 1969). In his seminal work, Simon argued that design is about "*changing existing situations into preferred ones*." This defines design by a reference to existing and preferred states of affairs, but it also mentions an action, change from a state to state. While this definition leaves little room for disagreement, it also remains quite abstract.

In engineering design, there are several widely used text books that all include their own definitions of design. Starting from a senior proponent of design methodology, Archer provides an elegant three-part description design (Archer, 1965). According to him design is an activity that produces "*a prescription or model for a finished work in advance of its embodiment.*" The elements are thus prescription and expectation of the embodiment. The third necessary condition is that the outcome must have some level of novelty in order to be considered as a product of a *design* process (design vs. replication). Archer's definition clearly has some merit, but has problems dealing with the types of conceptual design that provide no embodiment or with prototyping that produces the embodiments almost ahead of the design (see p. 28).

Pioneers of the German mechanical engineering tradition, Pahl and Beitz define design as an application of *"scientific and engineering knowledge to the solution of technical problems."* This takes place in a process where solutions are optimized within "*requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations*." (Pahl, Beitz, Feldhusen, & Grote, 2007, p. 1). This might stand as an accurate description of what engineering design has been some time ago. From an American perspective of design thinking, Ulrich and Eppinger (2008) provide a description of product design, in which "*[design] plays the lead role in defining the physical form of the product to best meet the customer needs. In this context, the design function includes engineering design (mechanical, electrical, software, etc.) and industrial design (aesthetics, ergonomics, user interfaces).*"

I believe that all referenced descriptions of design capture some parts of design, but my view is closest to Archer's. In the context of this work, I see design as **intentional human activity** attempting to create something **novel** and **desired**, regardless of the exact physical outcome. The Pahl and Beitz view is unacceptable because it is too rigid and sees design an optimization problem (see 1.4.2). The Ulrich and Eppinger definition is too product centered and too limited in taking the customer needs as a given variable.

1.1.1 Research and design

After providing some estimates what design is, the next step is find out how to study it. I will start the discussion about research and design by looking at how scientific thinking about design has evolved this far. A short history of how we have come to this is presented by Cross (1984). In his edition about design methodology he describes four generation of design thinking, with particular flavors indicated in parentheses:

1) 1962-1967 **Design methods movement** (prescription)

2) 1966-1973 **Figuring out the design problem** (description)

3) Late 70's **Analyzing the nature of design activity** (observation)

4) 1972 – 1982 **Philosophy of the design methods** (reflection)

Even if this only presents an arbitrary 20 years block from history, it also presents a regression from prescriptive, rational positivism to descriptive, critical reflections. Unfortunately there are no comprehensive reviews of the later period, which is strange considering the short history of this art. For instance, Design research society was established in 1966 after in 1962 the first conference on design methods was held and considered a success (Cross, 2007). Important and more recent step was the introduction of Design Studies journal in 1979, which has served to consolidate the design research discipline; although it questionable has the field become any more cohere since then. The continued interest in design methods and research was also indexed by two design conference series that started in 1980's; American Society for Mechanical Engineering's Design engineering technical conference ASME DETC (1989) and International Conference on Engineering Design (ICED since 1981) currently run by Design Society, both still going strong.

Talking about design as a research subject also calls for determining some approach for design research. My intention is not to exhaust all insightful design theorists. I have chosen to quote Fallman, who has recently analyzed the area of interaction design using a triangular model of design research (Fallman, 2008). His model is illustrated in Figure 1.2 on the next page. His framework positions design using three pivot points: design **research** or studies, **art** and exploration, and design **practice**. He argues that design research typically creates a trajectory or a loop that touches the two of these ends.

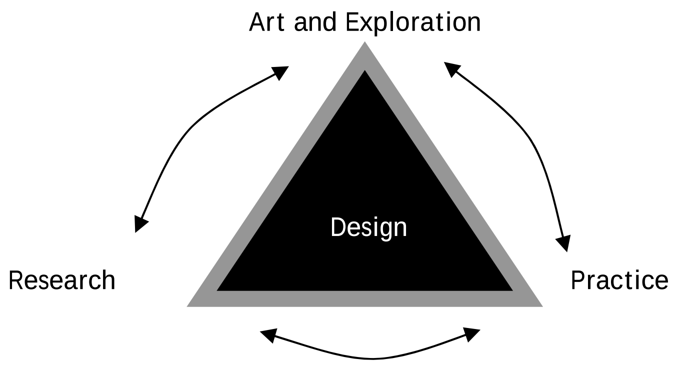

Figure 1.2 Triangular model that positions design research by Fallman (2008; adaptation of Figure 1) showing how research can connect to other design activities.

In the model of Fallman (2008), design research is a distinct activity with the goal of understanding and explaining design. Design research serves principally the interests of the scientific community. Through scientific methods, design research attempts to produce new knowledge about design. This makes design *research* distinct from the *explorative* and *practical* dimensions of design. According to Fallman *explorative* or *artistic* design seeks to provoke thoughts of critics and citizens at large by displaying new and radical ideas. It seeks to transcend the existing state-of-the-art and explore possible futures. Design *practice* aims to create and refine artifacts that please the customer. The success of this practice is dependent on designs that should be understandable for large publics and customers. Management writer Drucker (1993) would call this requirement *receptivity*.

The research corner of Fallman's triangle still leaves plenty of room for research to operate in. Krippendorff (2006) has analyzed the spectrum of different research interests. Building on the definitions provided by Cross (2000), he proposes three categories of research action: *science of design*, *science for design*, and *design science*. Starting from the last, Krippendorff argues that design science as a systematic and scientific inquiry into how one should design things was tried and did not provide the desired outcome (referring to the design methods movement). Science *of* design refers to the investigations of design in which the motivation originates from some other discipline, say sociology, cognitive psychology, or artificial intelligence. Design is studied to see how it is best described by some scientific discourse. For Krippendorff this kind of inquiry builds knowledge *about* design, but not necessarily *for designers*. Finally, science for design is a type of research that refers to a continuous self-reflective reproduction of design practices that have been found beneficial by a systematic review and evaluation. Krippendorff sees that this kind of inquiry best serves the interests of the design community and the development of design discourse.

1.1.2 What is it to design?

As the previous paragraphs provided some generic account of what it is to design, the next step is to introduce a more extensive vocabulary for describing design activity. What kinds of vocabularies have been used in design and how do they differ? If we start with descriptions that are especially about design, I again refer to Fallman (2003) who has analyzed different approaches to design. According to him, the approaches fall into three categories: conservative, pragmatic, and romantic. However, these terms have some unwanted connotations and I prefer to call 'conservative' rational, 'pragmatic' situated, and 'romantic' inspirational. The reason is that these terms have more appropriate equivalents in psychological and social theories of creativity (e.g. in Weisberg, 2006) than the labels Fallman has chosen. These accounts populate Table 1.1 below.

Table 1.1 Three accounts of design by Fallman (2003) reorganized and relabeled.

Definition of	**Rational account**	**Situated account**	**Inspirational account**
Designer	An information processor; a 'glass box'	A reflective, know-how, a self-organizing system	A creative, imaginative genius; an artist; a 'black box'
Design problem	Ill-defined and unstructured, to be defined	Unique to the situation, to be set by the designer	Subordinate to the final product
Process	A rational search process; fully transparent	A reflective conversion, a dialogue	Largely opaque, mystical
Design knowledge	Guidelines, design methods, scientific laws	How each problem should be tackled, compound seeing, experience	Creativity, imagination, craft, drawing
Product	A result of the process	An outcome of the dialogue	A functional piece of art
Resemblance	Engineering, optimization	Bricolage, human sciences, sociology	Art, music, poetry, drama

Fallman (2003) argues that the rational perspective describes the design process as a disciplined application of methods. The careful use of design methodology enables the designer to produce solutions to design problems. In detail, it is assumed that the process starts from a set of requirements and in a rational, transparent way proceeds towards the design solution. The key behaviors in design are analysis of the problem and synthesis of a solution. It is assumed that the design methods can be learned and successfully applied to all problems. Described in this way, this view resembles Krippendorff's design science mentioned earlier.

According to the situated account, "*design is about being engaged directly in a specific design situation.*" (Fallman, 2003 p. 227) In this account designers do not solve problems, instead they become engaged in a process of interpreting, framing (Ylirisku, Halttunen, Nuojua, & Juustila, 2009), and making meaning out of the design situation. In a reflective practice (Schön, 1995) designers embrace the design situation and try to make most out of it by examining the situation from multiple perspectives. Hence the required skill is a not problem-solving technique, but designer's success depends on constant self-reflection and evaluation. The skills of the designer are intuitive and tacit, the designer carries out design like other people carry out their daily routines. As a research approach, this seems most compatible with Krippendorff's science for design.

The third account of design from Fallman is inspirational. This account presents designer through a stereotype of creative genius. The designer may be inspired by the design challenge and the situation, but design itself involves something mystical. In this view, design is not something that could be scientifically grasped or turned into a method. The creative spark is something that comes and goes without a explanation, in a similar way to creative inspiration provided to ancient Greek poets by a muse, the offspring of Mnemosyne, the goddess of memory.

Although the analysis of Fallman has a merit for capturing a variety of attitudes to design, it has some issues. The primary question is that are these accounts valid descriptions of what researchers taking interest in design thinking would subscribe to descriptions? Is there external validity? This seems especially problematic with the inspirational account, although some interaction designers, such as Gaver, seem to hold these kinds of views (Gaver, Dunne, & Pacenti, 1999; but see Zimmerman, Forlizzi, & Evenson, 2007). From Fallman's description, it is clear to see that the rational account of design is connected to cognitive psychology and design cognition. In cognitive psychology, design has been considered as problem solving. Compared to some more distinct problem areas, such as chess or mathematics, design has been labeled as ill-structured problem domain (Newell, 1969; Simon, 1969, 1973), ill-defined (Reitman, 1965) or wicked (Rittel & Webber, 1973). This ill-structured nature of design problems denotes that solving them is different from solving well-structured problems as they are incompletely defined, with evolving constraints and vague initial and goal states. These concepts will be presented in 1.4.2.

Secondly, what are the relations of the account theorically? Can the different accounts co-exist or are they mutually exclusive. For instance, could the inspirational account be turned into a scientific theory? Is either rational or situated account more accurate or are they just describing different sides of the same coin? These questions will remain open for the rest of the introduction, but I will refer to them in the following chapters. I see that they nicely illustrate the different attitudes that are displayed in design theorizing. For now, it should be stated that the view of design promoted in this dissertation is closest to rational, but with a desire to merge with the situated account.

1.1.3 Design cognition research

This thesis aims to make a contribution to the science of design. In this thesis, I study conceptual product design from a design cognition perspective. Design cognition is a relatively new and open set of explanatory concepts and methods for describing design. As the name implies, it is based on the cognitive theories of behavior and mind (e.g. as in Johnson-Laird, 1980; Norman, 1981; Pylyshyn, 1984), providing psychological theories from an information-processing point of view. When cognitive science emerged during 1970's, the idea of a psychological description of design followed soon after (Thomas & Carroll, 1979). The term 'design cognition' first appeared in 1990's when the term was utilized by Oxman and Oxman (1992) and Lloyd et alia (1995), although studies that would meet criteria had been published earlier on (e.g. in Lawson, 1979). In 1994, Oxman and Lloyd's papers, Georgia University of Technology in United States organized a workshop called Design Cognition and Design Education Workshop. Lot of new theorizing has since emerged applying various cognitive approaches that could be labeled as design cognition, but no coherent and unanimously accepted theory of design as cognitive activity exists to date.

Why do we need design cognition or psychology? For several reasons, I believe we can benefit from design cognition. First, design cognition aims to produce scientific theories of design and thus inform design *thinking*. It contacts our 'need to know' by providing new descriptions of design as a human activity, revealing aspects of design that would otherwise remain unknown. Secondly, design cognition can via methodology development and education contribute to design praxis, or *doing*. In the face of numerous new design methods and in the constant pressure to be more creative, practitioners and organizations need objective information to help steering the development of design practices. Design cognition presents a rational stance to design and in particular to design methods, a way to study methods, to establish design practices based on firm evidence and testable theory.

1.2 Scope

This dissertation focuses on a presenting a cognitive model of IG in the context of early product design. Idea generation is defined in a narrow sense to include activities that aim at producing a large amount of concept candidates, without selection, evaluation, or reflection on the ideas. During the early design process, the ideas are preliminary, abstract, and often not very convincing. This thesis is primarily theoretical, although heavily grounded in scientific literature and empirical observations documented in the constituent publications. The discussion included in this thesis follows these publications, which consider several aspects of design, but in this thesis I will concentrate in the cognitive core of design.

This thesis can also be defined by exclusion of several associated topics, which were not considered crucial enough. This work is not about individual differences in creativity, process models of design, development of new design methodologies, or an establishment of new cognitive vocabulary. This work does neither concern innovations nor their management. An innovation, which can be defined as an idea that can be commercially exploited (Rogers, 1995), is not considered to be particularly different from other ideas. It is assumed that the difference between an innovation, an invention and 'just an idea' is not psychological, it is practical and culture or market-determined. The psychological processes related to turning ideas into innovations are excluded from this work.

It needs to be emphasized that my formulation of 'ideas' and 'idea generation' is also a rather clinical one. In contrast to everyday discourse, idea here does not refer to a particularly novel, outstanding, or ground breaking discovery. In studies of idea generation conducted in research laboratories, ideas are often very simple, everyday, and conventional. Ideas that are collected experimentally can even have probability distributions! Of course, some of the ideas can be exceptional, but that is not a criteria here.

As there are several quite distinct areas of design, a question arises how domain independent are theories of design? To what extent are theories of architecture also applicable to software engineering? This is a very important question that has also been considered in the literature (Akin, 2001; Visser, 2009). I have chosen to include studies from several areas of design and I will discuss the consequences of this decision in the Conclusions chapter. A related issue is that this thesis is specifically about the design of physical, functional products. However, in many cases, descriptions of design I provide might well be about software products, service concepts, or business models (see Sawhney, Wolcott, & Arroniz, 2006). The psychological principles and constraints that underlie inventions should be shared across different domains.

1.3 Characteristics of Conceptual Design

1.3.1 The role of conceptual design

Conceptual design is commonly placed among the fuzzy front-end design activities (Khurana & Rosenthal, 1997; S. E. Reid & de Brentani, 2004). For instance, a textbook widely used in Finnish product design education by Ulrich and Eppinger (2008) describes a linear, cascading design process in six major phases, one of them being concept development. This generic design process model is shown in Figure 1.3. The name 'generic' implies that it is an idealization of realistic processes and in reality, concept development may not be so linear process nor without variations. However, for the present work, this general model provides a framework to which empirical studies of idea generation can be related to. This point of attachment is the *concept generation* step in the concept development phase.

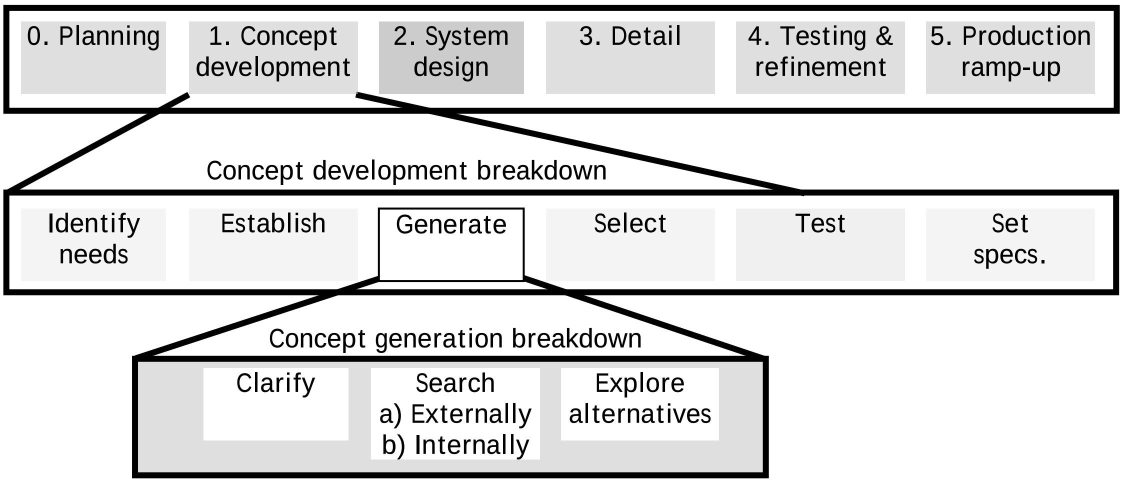

Figure 1.3 Generic prescriptive model of product development process highlighting the concept generation phase. Adapted from Ulrich and Eppinger (2008).

The Ulrich and Eppinger model is of course not the only model for the design process. For instance the German organization Verein Deutscher Ingenieure (VDI) has specified its own reference model VDI 2221 for product design (Wallace, 1993). VDI 2221 is a prime example of a *prescriptive* design model, intended to instruct designers. For more prescriptive models, see Cross (2008). From another point of view, Keinonen and Takala (2006) have analyzed the position of conceptual design from the perspective of a major design organization (a 'big business' view). They argue that there exist three types of conceptual designs: *vision*, *emerging*, and *product development* concepts. This considerably broadens the scope of what conceptual design is about. These three concept types have different outcomes and are differently important for the companies.

Vision concepts are strategic tools which allow companies to forecast and plan for the future. This can involve probing new business areas and new kinds of products. These concepts are typical for car and consumer electronics industry who frequently display prototypes at exhibitions and similar public relations events. These prototypes are hardly even considered eligible for production, but are used to shape the company brand through publicity. *Emerging concepts* come closer to real products. Their function is to open up channels to meet new user segments, new user needs, or to reform existing product platforms. Emerging concepts have important business value and contain features that can be integrated into existing products or shaped into new products swiftly. *Product development* (PD) concepts correspond to the definition of concept used earlier by Ulrich & Eppinger. PD concepts are created in order to define the future product. The aim is to select and refine generated concept ideas into finalized products. When PD concept design begins, it is already known what sort of product is being sought, in terms of how it should fit among the existing product catalogue of the company. (Keinonen & Takala, 2006)

Finally, a common term that is mentioned sometimes in literature in relation to conceptual design is *divergent thinking*. Divergence refers to spreading or branching, to a process that opens up many new directions. In product design, this is what should happen during concept development. The term divergent is commonly associated with so called 'creative' thinking (Guilford, 1950) and can be used synonymously with 'creative design'. Some people have also equated divergent thinking with simple associative thinking (Saariluoma, Nevala, & Karvinen, 2006). If we maintain the original definition of opening (divergence) and closing (convergence) opportunities, it is not evident that this happens only in conceptual design. Due to many possibilities of misinterpretation I will avoid using the concepts divergent and convergent design in this text.

1.3.2 Methods of conceptual design

Methods are procedures or instructions that should help a person to accomplish some task. In contemporary literature, there are also methods associated with conceptual design. These methods might also be called innovation methods as their aim is to facilitate the production of competitive products. From a basic research point-of-view, they might be labeled as tools for creative, lateral (De Bono, 1970), bisociative (Koestler, 1964), divergent (Guilford, 1950), chaotic (Finke, 1996), impossibilistic (Boden, 1999), or out-of-the-box thinking. Due to the nature of conceptual design, these methods do not guarantee any solutions, they only help and facilitate the discovery of ideas.

Next I will introduce some idea generation methods for conceptual design. They seem to have some influence on real IG practices (Berkun, 2007; Perttula, Poskela, Ekman, Sipilä, &

Kuitunen, 2005), hold a position in text books, and have directed design IG research. For these reasons I see important to include them here. The methods come from two design traditions, product design (PD) and interaction design. The methods mainly serve the IG generation function, even though many methods go beyond that. These methods from have been selected by relevance and prominence in the textbooks (Pahl et al., 2007; Ulrich & Eppinger, 2008). A wide coverage of idea generation methods in general is not feasible, as the review by Smith conducted in 1998 (G. F. Smith, 1998) already identified 172 methods and more have been introduced since then. Shah (1998) analyzed IG methods commonly involved in engineering design, creating a taxonomy shown in Figure 1.4. This classification starts from a division into intuitive and logical models, including over a dozen different techniques. The methods I will discuss and reviews in thesis are all intuitive. Although the rationale of the classification may be disputable and I will apply a slightly different scheme later on, it nicely illustrates the variety of approaches.

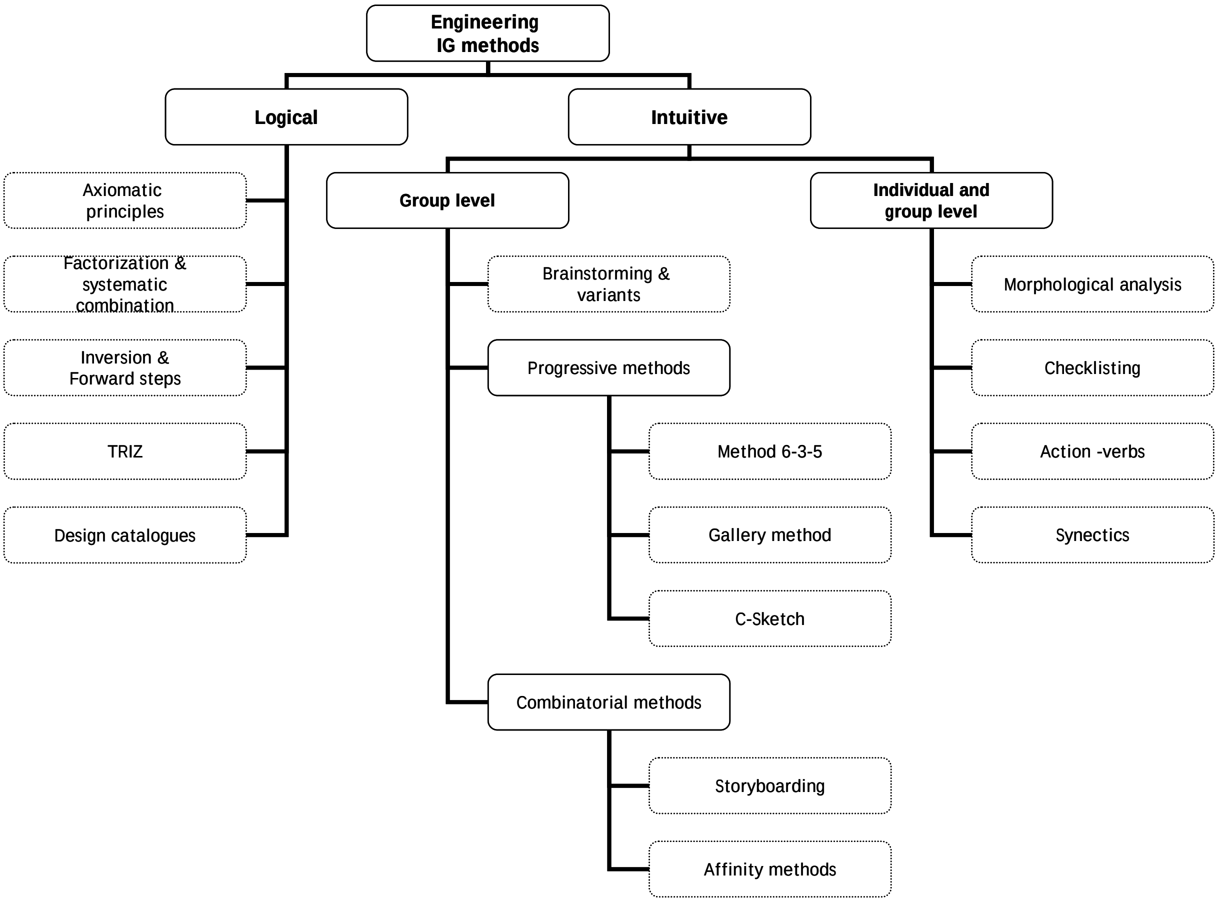

Figure 1.4 Classification of IG methods for according to Shah (modified from Figure 1 of 1998).

Product design idea generation methods.

Brainstorming (Osborn, 1957) is inevitably the best-known method for creative group work and has been also adopted by the product design community. Brainstorming describes how a group of people should collaborate in order to increase their productivity. Invented in 1930's, the original concept of Brainstorming included several normative guidelines as how an effective idea generation session should be conducted. However, Brainstorming has also become a rainbow concept which covers almost all forms of small-group practices oriented towards producing something new. The popularity of Brainstorming has evoked considerable attention from researchers. In social psychology, a selection of cumulative studies dealing with Brainstorming exists and is sometimes referred to as the Brainstorming literature (Sutton & Hargadon, 1996). The main findings of these studies were summarized in 1987 by Diehl and Stroebe (see Diehl & Stroebe, 1987; Stroebe, Diehl, & Abakoumkin, 1992) who claimed that the organization of group work commonly applied in Brainstorming was actually decreasing group creativity and productivity. Since then, identifying the problems associated with the traditional Brainstorming has fueled the development of many variants that usually utilize computer software. These variations have proven effectiveness (see e.g. Dennis, Aronson, Heninger, & Walker, 1999; Paulus, Nakui, Putman, & Brown, 2006; Potter & Balthazard, 2004), but have gained only little popularity.

The next example of intuitive methods associated with product design is *Method 6-3-5* (Pahl et al., 2007; Rohrbach, 1969 in Pahl and Beitz, 2007). Its name refers to a procedure in which 6 participants are initially given 5 minutes to produce 5 ideas. Ideas are written on papers that then are circulated between the participants. They provide inspiration and starting points for the following five minute rounds. This aims to support systematic exploration of all initial ideas. *Synectics* is a method introduced by Gordon (1961) that uses the idea of connecting familiar with unfamiliar things in order to stimulate idea generation. This idea is known as analogical or metaphorical thinking and would be psychologically described as the capacity of transferring knowledge across domains, e.g. matching a mobile navigator design to cook book recipes. *Morphological analysis* comes somewhere in the middle of intuitive and logical methods. Created by Zwicky (1969), it is intended to assist in exploring the problem dimension (problem space) by listing of the relevant attributes or parameters. After the problem dimensions are decomposed, the emerging matrix is filled with potential solutions, creating forced associations that may yield some new insights about the problem see (for more information, see Cross, 2008; Ritchey, 2002).

Idea generation tools are artifacts or practices that can help in IG. *Sketching* is a fundamental design activity (Goel, 1995; Suwa, Gero, & Purcell, 1998). In design cognition research it has been mainly considered as an external memory (see Newell and Simon, 1972), but it is argued that sketching can qualitatively change the nature of design IG (see Fallman, 2003). In some areas of design, including architecture and industrial design, the final output of the work is represented in graphical form, nowadays commonly finalized in computer-aided design (CAD) environments. In the conceptual design phase, sketching and quick illustration can be an intermediate material to save time and provide a more detailed documentation medium than text alone (McKoy, Vargas Hernández, Summers, & Shah, 2001; Song & Agogino, 2004). Due to the essential role of sketching, there is an extensive literature about sketching that considers both its pragmatic, cognitive, and creative aspects (Goldschmidt, 1991; Kavakli, Scrivener, & Ball, 1998; Shah, Vargas Hernandez, Summers, & Kulkarni, 2001; van der Lugt, 2002).

Prototyping is a definitely designerly way of working in PD. Prototyping can provide information for the design process during many parts of the process, including conceptual design (Pahl et al., 2007). As Ulrich and Eppinger (2008) point out the word prototype has various meanings and refers to both action (to prototype) and an object (the prototype). They also discuss different functions that prototypes have. Using two dimensions, called physicality and comprehensiveness, they present three feasible clusters of prototypes. *Comprehensive physical* prototypes are examples of extensive pieces that can be used for *communication* (from design team to outside), *integration* (between design teams), *learning* (within design team), and as *milestones* (an acid test). For instance, previously mentioned vision concepts in car industry are prototypes in this sense (cf. Keinonen & Takala, 2006). *Focused physical* prototypes are for communication and learning whereas *focused analytical* prototypes are for learning purposes (‘design exploration’). They usually target some parts of the concept and may include some physical approximation of the future product.

The practice of focused physical prototyping used for learning is beautifully reflected in two volumes by Kelley (Kelley & Littman, 2001, 2005). These books describe product development success stories that originate from prototype-based conceptual design. As building full-blown prototypes is time consuming and expensive, concept designers commonly seek out ways to do rapid or *rough prototyping* which is faster and coarse, but still effective (Reinikainen & Björklund, 2008; Sanders & Dandavate, 1999). The idea of rough prototyping is to try out design ideas as early as possible and learn from the outcomes. It tends to produce focused physical prototypes, as the comprehensiveness is limited by the readily available components. Notice that the term rapid prototyping is also used outside conceptual design in relation to embodiment design (e.g. see Kochan, Kai, & Zhaohui, 1999).

Physical prototyping requires some flexible material for building prototypes. This has lead designers to develop specific prototyping kits, such as make-tools (see Mattelmäki & Battarbee, 2002; Sanders & Dandavate, 1999), which allow quickly building approximate models of a concept. They can still serve as a starting point for discussion and reflection about the designed artifact. ‘Physical’ prototyping is not limited to physical products. The term Bodystorming has been introduced to describe prototyping applied to designing user experiences, particularly in relation to different services (Buchenau & Suri, 2000). Incidentally the same term has been also used in another sense related to interaction design (Oulasvirta, Kurvinen, & Kankainen, 2003) to describe an IG practice resembling brainstorming but simulating or taking place in some real world context.

Existing and competing product examples are sometimes introduced to the IG process not only for benchmarking, but for inspiration. Different kind of *stimuli* in a design IG process have been quite extensively investigated (Benami & Jin, 2002; Perttula & Sipilä, 2007; Shah, Kulkarni, & Vargas Hernandez, 2000). Commonly practiced benchmarking could also be said to achieve this purpose. Several investigators have studied how related products and unrelated stimuli included in design IG sessions can influence the design process. More directly applicable solution can be provided by reversed *biomimicry*. This means studying and evaluating biological forms and functions, for instance, bird flight, in order to use this as an inspiration for design (Benyus, 2002; Volstad & Boks, 2008).

Interaction design idea generation methods.

Interaction design refers to the design of interactive products and interfaces. These are commonly associated with computer software products, but nowadays more and more found in many physical products and embedded systems. The selection of methods presented in the field of interaction design is impressive given its relatively short history. For instance, prototype-based iterative testing and development has been a prevalent method already for some time in interaction design, whereas it is a relatively new idea for conceptual PD. In interaction design, there exists a culture of visual software concept demonstrators, non-interactive communication tools (Wolf, Rode, Sussman, & Kellogg, 2006). On surface level they correspond to visionary concepts of automotive industry, but they are not functional. Within interaction design, *user-centered design* (UCD, e.g. in ISO, 1999) or *design for user experience* (DUX; Hassenzahl & Tractinsky, 2006) are currently important design approaches. It has been argued that a transition from technology-centered to human-centered development of products is a fundamental paradigm shift for product design as well (Krippendorff, 2006). However, in the context of the present thesis UCD or DUX are not particularly interesting. The reason is that the user-grounded requirements of usability or acceptability are in the present theory considered to be equal to all other design constraints, for example technological ones.

The user-related requirements have an indirect influence on design IG. This is because even discovering user constraints has proven to be a challenge. For instance, in software design, technological development has not been as important as acknowledging the need for some product or service (e.g. the rise of social media and Facebook). In order to handle the user needs, several techniques that provide user-needs input for design IG have been introduced. The interesting methods belong to a cluster called *user-inspired design* (UID, concept is derived from Mattelmäki & Keinonen, 2001). These types of methodologies produce information, or inspirational material, that can be exploited in the IG phase of conceptual design. These methods overlap the combinatorial methods branch of the intuitive group methods presented by Shah (1998) in Figure 2.1.

Although UID is not a clearly defined field, in my opinion there are some published methods that fit this function. From a set of inspirational methods, *probes*, *extreme-user method*, and *video-based methods* are considered. Cultural or empathy *probes* are a method for learning about how a segment of users lives, how they perceive their daily life, and possibly how they use existing technologies (Gaver et al., 1999; see also Mattelmäki & Battarbee, 2002). Physically, probes are a collection of simple artifacts, such as notebook, map, and a disposable camera. This set of items allows users to record facts and happenings of their daily life independently. Technology probes are a separate technique that some novel technology to the package (Hutchinson et al., 2003). Designers prepare the probes, deliver them to users, and collect them. The method is essentially inspirational because there is no formal method to analyze this input. Instead, the probes are used as stimuli for designers to help provoking ideas that may relate closely or remotely to the probed users.

Extreme-user method also tries to ground conceptual design in the lives of users (Holmquist, 2004, 2006). In this method, a group of people are selected because of their special interests, hobbies, or conditions. The practices of this group, called extreme users, are investigated using some qualitative method (see subsection 2.2.4). The goal is to analyze their common interests or practices. For instance, people practicing lomophotography or having reptilians as pets have been studied (Jacobsson, Ljungblad, Bodin, Knurek, & Holmquist, 2007; Ljungblad, Hakansson, Gaye, & Holmquist, 2004). The responsibility over the design remains with the professional designers, as this approach does not require users to participate in design or to generate design themselves, unlike different *participatory design* (Kensing & Blomberg, 1998) or *lead-user design* (Hippel, 1977; Urban & von Hippel, 1988) would require.

Video is a medium that is all the time getting more and more attention in interaction design. Video can serve multiple functions in a design process. As a way of user-needs and task analysis, video-based ethnography records and communicates the users' life to the designers. In participatory design, video is often used to record the design sessions and arising ideas. The power of video communication is leveraged in usability studies, which can employ video to highlight a usability problem. And the video has also the capability to communicate concepts and ideas that are otherwise just fiction, as highlighted earlier when discussing video demonstrators as visionary concepts. Demonstrator videos in scenario-based design can depict futuristic interaction sessions taking place with a concept product or a service (Ylirisku & Buur, 2007). In particular the ethnography function leads the way to idea generation and provides inspiration for design.

1.4 Background for Design Cognition

1.4.1 Cognitive theories

I claim that the theory presented in this thesis is ‘cognitive’. This should be complemented by saying that approach is symbolic cognition, or traditional computationalism as defined by Newell (1980) For those unfamiliar with this discourse, it need to be said that cognitive theories can address very different levels of information processing and there is no clear consensus of what these levels are or what do they stand for. For instance, Anderson (1990) reviewed slightly different proposals for the types of cognitive theory from six different authors, including himself. To illustrate the opportunities for a cognitive design theory, I have chosen some of the descriptions mentioned by Anderson (*ibid.*) and summarized them in Table 1.2 below:

Table 1.2 Levels of cognitive theory according to various cognitive scientists adaptod to design context. Adapted from Anderson (1990) with modifications.

Chomsky, 1957	Pylyshyn, 1984	Anderson, 1990	Description “*design example*”
Performance:	What happens in design, phenomena of design “*Ed is working with a pen and paper*”		
Competence: Description of how design is possible	**Semantic**	**Rational/ Adaptive**	Abstract descriptions of design, “*Ed is sketching a paper machine*”
	Algorithm	**Algorithm**	Computational description of how design is carried out “*How Ed re-uses his existing knowledge and skills to create the design*” Inferred from a protocol
	Functional architecture	**Implementation**	Computational implementation of the theory “*How information about paper machines and operations required for design reside in cognition*”
	Biological	**Biological**	Foundations of design in human biology “*How brain, hand muscles, and other body parts operate to produce the design*”

Anderson includes four different levels of cognitive theory: rational, algorithm, implementation, and biological levels. These fairly well aligned with other prominent cognitive scientists, named in the previous table.

The theory of design I defend here is an algorithm level description of cognition, corresponding to the approach presented in the constituent publications I-III and VII. It is assumed that this is the level from which some results of operating algorithms are available for conscious reporting and cognitive scientists can acquire this information by protocol analysis (see section 2.2.3). One could also describe my theory as heuristic in contrast to detailed as I will remain on a fairly abstract level and not present more precise mathematical or algorithmic formulation than what has been used in the publications. I attempt to construct through examples and logic a theory of idea generation that has determined limits. In several occasions, this thesis includes references to the performance and rational levels, but the main interest remains at the algorithm level. The implementation and biological levels are not considered.

The biological level does not appear relevant for the purposes of this study, although there are some related studies that investigate the relation of creative work and brain activity (Chávez-Eakle, Graff-Guerrero, García-Reyna, Vaugier, & Cruz-Fuentes, 2007; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). This resembles Anderson's (1990, p. 26) belief that "*for many purposes … such a physiological base would be excess baggage*." The functional architecture, or implementation, is important and will be necessary step in the future to evaluate the algorithm level theory. It should be noted that a mathematical model (applying set theory) for creative design has been proposed recently proposed (Hatchuel & Weil, 2009), but it does not fit the desired *psychological* modeling scheme at all.

1.4.2 Concepts of design cognition

Scientific enterprises are usually characterized by the concepts and theories used to describe their research subject. In natural sciences, these concepts and theories are commonly expressed as mathematical formulas, theorems, or computer models. Some consider this mathematical approach as the hallmark of science, or at least as a demarcation criterion for 'hard' science. However, the history of science shows that even the so called laws of nature formulated in exact formulas may prove wrong. For instance, Newtonian physics have been somewhat replaced by quantum physics for increased accuracy but at the cost of additional complexity. In some aspect the old Newtonian theory is better because is easier to apply and understand. And in order to be useful, the formulas need to be understood and easily applicable.

Concepts and theories of design cognition advocated here belong to the 'soft sciences' category. In this thesis, no proofs or equations of idea generation will be presented. Instead, design will be described by concepts that attempt to help in *understanding* the process of design from a psychological perspective. This may lead to more formal approaches in the future. Along with the previous comparison of Newtonian and quantum physics, I claim that from the present perspective, this kind of theory is good in the current circumstances, even if it is not an ultimate one.

My next step is to introduce the vocabulary that I will use in this work to describe conceptual design with. The concepts are mainly derived from the vocabularies of traditional cognitive science and problem solving. I do not claim that they are all necessary or even adequate for describing issues of interest, but they are necessary to explicate how the design-as-problem-solving view has evolved. The main concepts new to IG research start from page 36 and concern the role of memory in IG.

It must be noted that only a fraction of all concepts central to cognitive psychology can be considered here. General psychology covers topics from visual perception, attention, speech perception and production to emotions and decision making (see e.g. Eysenck & Keane, 2000; Quinland & Dyson, 2008). I have chosen to focus on the concepts that are most suitable for describing design IG and which have been used in the constituent publications. The excluded topics are considered to be less relevant for the present theory. Expertise presents one boundary case that bears significance and has traditions in design studies. I have chosen to omit it here, although I make some references to it. For those unfamiliar with the topic, I recommend become acquainted with the literature (see e.g. Ball, Evans, Dennis, & Ormerod, 1997; Casakin & Goldschmidt, 1999; Chi, Glaser, & Farr, 1988; Cross, 2004b; Ericsson & Smith, 1991; Popovic, 2004).

The explanatory concepts used in design cognition are derived from a dichotomy of *processing* and *knowledge*. This distinction is derived from the computer metaphor (Newell, 1980), an early model of human cognition inspired by digital computer and the Turing machine. According to this view, all information processing can be divided between two theoretical entities; data structures and operations on data structures. The information processor, for example a computer, a Turing machine, or a human, is constantly processing information according to some procedure, algorithm. For instance, if numbers 1 and 2 are the data and an operation 'sum up' is defined, new datum, number three, can be produced by procedure `sum up(1,2)`.

When this thinking is applied to design cognition, it becomes necessary to find a framework for describing the design activity as a whole, depict the steps in this activity, and present a theory of design knowledge. Design activity has been repeatedly described as ill-structured problem solving in cognitive literature (Newell, 1969; Newell & Simon, 1972; Reitman, 1965; see Visser, 2009), inspired by the progress that had been made on the so called well-defined problems. Later on, these principles have been applied to ill-structured problems and thus it is necessary to introduce them here, although they may at first seem quite detached from design.

The concept of problem solving is fundamental for cognitive psychology and the early forms of artificial intelligence. The idea is that a problem consists of an *initial state* and a *goal state*. The problem exists if the stages differ and the transition from the initial state is non-trivial. The final part of the problem description is the selection of *operations* that are required to reach the goal state from the initial state. In this formalism, problem solving is a process of moving from the initial to the goal state by applying selected operations.

A simple example to illustrate well-structured problem solving commonly used in the literature is a game. In the Tower of Hanoi, three discs of increasing size are placed on one of three pegs and must be moved from the left peg to the right peg so that only one piece is moved at a time and a larger piece can never be placed upon a smaller one. If you attempt to solve this task mentally you will probably find it very difficult if not impossible. However, with help of physical objects or a sketch, such as that displayed in Figure 1.5 below it is much easier to see how the solution can be attained.

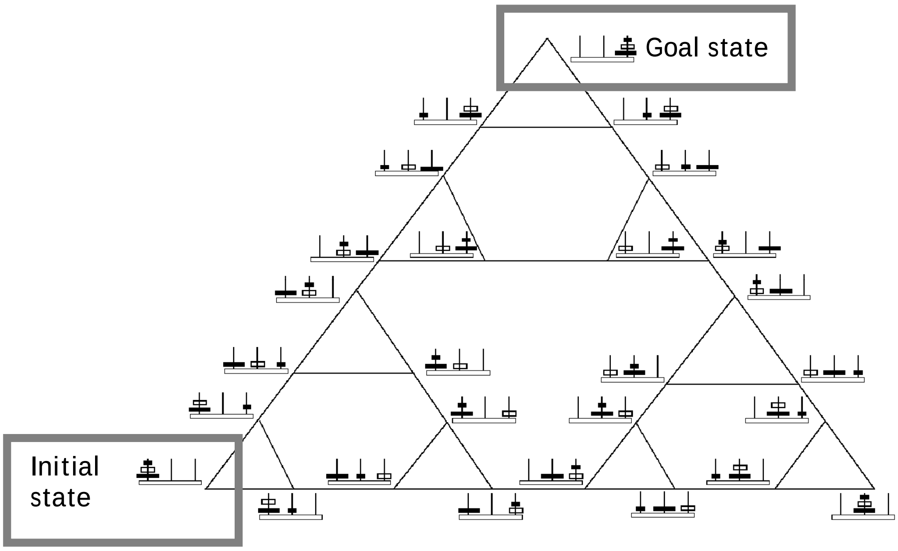

Figure 1.5. Visualization of a problem states for the Tower of Hanoi game. The initial state is in the bottom left of the pyramid, the goal state on the top.

The problem visualization in Figure 1.5 shows that because the goal state can not be reached by one operation, many *intermediate states* emerge. *Problem space* is the combination of all possible problem states, including the initial, intermediate, and goal states. Problem solving is about *moving* or *making steps* in the space towards the goal state. Tower of Hanoi also illustrates the challenge in solving the well-defined problem. The problem is not about knowing how to do, as the operation is clearly defined, but in *selecting* the right operation in each turn. This is the problem of search associated with well-defined problems.

Search is an essential concept to describe problem solving. It describes how to navigate through the problem space and find the goal. Literature describes several ways how the search can be guided, how the operators are selected. It is assumed that there must be a feedback mechanism, a way to evaluate the progress. This is the distance to the goal as a consequence of applying a problem solving operation. Methods such as means-end analysis, hill climbing, forward or backward search, or heuristic search (Langley, 1985; Newell & Simon, 1972; Russell & Norvig, 2003; Simon & Newell, 1958) all describe different ways of guiding the search. Many of these algorithms have exact algorithmic formulations documented in literature and are excluded here.

A characteristic feature of well-defined problems is that the minimal amount of operations required to reach the goal can be calculated, e.g. following the right side of the pyramid in the example. This is the *optimal* solution for this problem. The performance of different search methods can be examined by comparing how close to optimal solutions they produce. From the perspective of artificial intelligence, the search methods fall into three different categories: *uninformed*, *heuristic*, and *fully informed*. Uninformed search is commonly labeled as 'brute force' method because it does not require knowledge, only a feedback mechanism to operate. In the Tower of Hanoi example, this would mean that all paths to the goal state are randomly tried until the difference to the goal is minimized to zero. This technique is considered to be a *strong* method because it is guaranteed to produce a solution.

Heuristic search relies on so called heuristic knowledge, commonly called 'rules of thumb' in deciding the next move. Heuristics are learnt rules that have a limited application. For instance, assume another game called the *Tower of Pisa*. Players of this game may have learnt a heuristic "*always move the small peg to the extreme right*" and try apply that rule to Tower of Hanoi. The heuristics can produce solutions more efficiently than uninformed search, but it can go completely wrong if the rules do not fit the *problem domain*. This is what happens with the Tower of Pisa heuristic above. This means that heuristics are *weak* methods, prone to err, in problem solving. Finally, there are fully informed methods that come closest to the traditional sense of knowing something. For instance, the set of procedures needed to solve Tower of Hanoi can be remembered and *looked up* from memory to quickly solve the problem. This search method is very vulnerable to changes, like the Tower of Pisa heuristic; knowledge may become outdated or obsolete if the problem space is changed but a little.

One evident point of criticism is that hardly any of real life problems are as simple as the previous example. More complex problems require more elaborate definitions of the initial and goals state, and more operations for completing the task. Some might say that they require knowledge more than search mechanisms. A very important part of any cognitive theory is a description of knowledge. In the Tower of Hanoi example, the problem has been represented and solved using a fairly limited number of components, three discs and pegs, and one rule. This is not much of a knowledge structure or a computational system. In cognitive sciences, concepts such as schemata and frames have been usually applied to describe more elaborative and structured combinations of knowledge (see, e.g. Eysenck & Keane, 2000; Russell & Norvig, 2003). For design, the psychological representation of design knowledge is necessary part of the theory but currently not very well understood. This is discussed in 3.1.3.

Another important addition of ill-structured problem solving theories is the introduction of multiple, independent 'problem' spaces. For instance, Klahr and Dunbar (1988; see also Klahr & Simon, 1999) have used concepts of a separate problem and solution space to describe how scientific discovery, or rule induction from empirical data, unfolds in an experimental setting. While design maybe is a more solution-oriented area than scientific inquiry (see Goel & Pirolli, 1992), Dorst and Cross (2001) have discussed the opportunities of a dual space search in design. They describe co-evolution of solution and problem space which takes occurs in the process. An important component in their model is constant search for surprises that could bridge the two spaces at some point of time.

This thesis attempts to extend the design cognition theory and hence it is necessary to introduce relevant new explanatory concepts. In this work, the concepts are psychological ones describing properties of human memory (for more information, see e.g. Baddeley, Eysenck, & Anderson, 2009; Quinland & Dyson, 2008). The story starts from the computer metaphor and from the concepts of short-term or *working memory* (WM), and *long-term memory* (LTM). The analogy to a 21st century PC would associate working memory with the random-access memory (RAM) and long-term memory with the hard drive. However, beyond these simplified functional roles, there is very little resemblance between human and computer memory. *External memory* (EM) concept is also sometimes used (Newell & Simon, 1972) to highlight how people external aids, such as Post-it notes and shopping lists, to overcome the limitations of WM and LTM. It must be stated that in this thesis, and in related theories of IG reviewed in section 2.4, it is assumed that even complex memory contents can be retrieved as quite perfect records of memory. This is somewhat problematic assumption is considered in Discussion (4.4).

Discussing the construct of human memory, we encounter several opinions about the nature of that system. First, the distinction between short and long-term memory is not a very clear one and psychologists still argue over the matter. While some have proposed very elaborate theories about the nature of WM, including an organization which divides it into four subsystems (Baddeley, 2000), even the existence of a short-term memory as a cognitive mechanism remains somewhat disputed (see e.g. Cowan, 2001; Unsworth & Engle, 2007). The debate boils down to the question can WM be considered as an independent storage system or is it a temporarily activated part of LTM. As this thesis is about applying memory concepts, it seems appropriate just to describe the *functional* properties that these two types of memory (WM and LTM) have, rather than dive into the theoretical debates about their nature.

WM is a system that can hold small amount of information for a short period of time. The label working memory is figurative, for it is important to be able to briefly retain some information available in mind, such as a new phone number when placing a call. The contents of the WM are typically eventually stored in and later retrieved from LTM, sometimes called permanent memory, which has a seemingly infinite capacity to store information. It is likely the primary storage of your own phone number. Despite the huge capacity of LTM, people often have problems remembering things. These can be attributed to two sources: either something has not been learned (does not exist in LTM) or it can not be accessed (retrieved from LTM). In contrast to computers, human memory works very differently, because it has adapted to solve very different kind of data storage problems than what a computer has been designed to (Anderson, 1990). For this reason, phone catalogues, and more recently Internet, can serve as *external memory* that can help to overcome these limitations.

The information contained in LTM must become available in WM before it can be utilized. This access is called search. The LTM search is guided by a set of search cues, for instance, Unsworth and Engle (2007) mention temporal, contextual, categorical cues. These cues are used to form a search set and this set is sampled for retrieving items (illustrated in Figure 1.6 below). To get the desired information into the search set for recovery, the initial search cues must include several attributes that are associated with the desired information. An important feature of human memory is flexibility, which shows in probabilistic retrieval and variable content addressing. While this can be a defect, as in the case of forgetting, it also offers good performance in a variety of situations in which computers can not operate very well in.

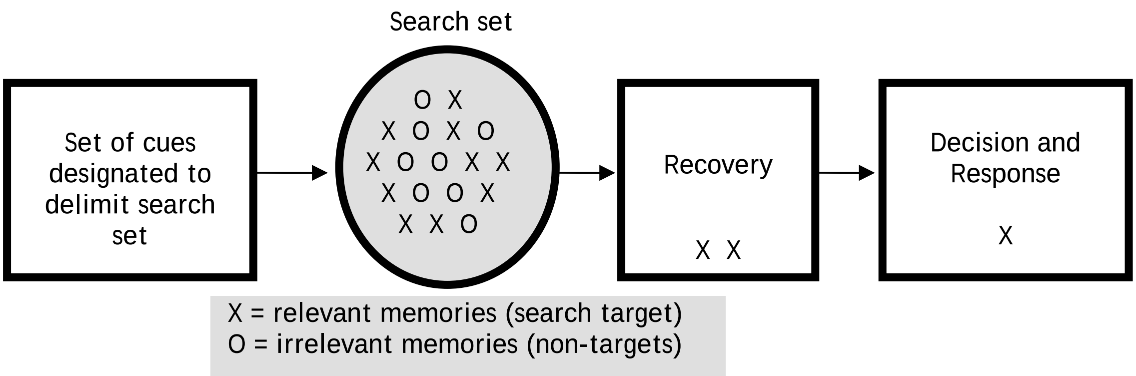

Figure 1.6. Memory retrieval process according to Unsworth and Engle (2007). Recovery from LTM is based on a sampling from a search set. The search set is delimited by a mandatory set of memory search cues. Targets and non-targets illustrate the challenge of recovering only task-relevant memories.

Another important question concerns the limitations of WM. It is said to be restricted in capacity but just how large is our working memory capacity (WMC) or how should be measured? After fifty years of study, the nature and size of WMC is still a debated issue in psychology (see, for instance, Feldman Barrett, Tugade, & Engle, 2004; Miller, 1956; Unsworth & Engle, 2007). WMC is typically measured in *chunks*. The fine feature of chunk is that it is not fixed to any particular type of information. For instance, place your finger on this page, mind the letters U, E, O, I, N, M, R, N, D, F, and close the page for ten seconds. Open the page again and try how many letters you can recall correctly.

The capacity debate goes back over 50 years (Miller, 1956) to the first approximations suggesting that WM can hold 7±2 chunks at a time. Modern estimates about WMC are modest and assume that you should remember at least 4 letters (Cowan, 2001). Remembering all 11 unrelated units of information clearly exceeds the capacity of working memory and hence they cannot be recalled correctly when they are prompted for. However, if you had tried to recall the word 'uninformed', a different kind of chunk composed of the same letters, the task would have been trivial. This means that the organization of knowledge can influence the outcome of our cognitive efforts. It has been demonstrated that WMC limitations can be overridden using a mechanism called chunking, which is commonly related to expertise in a certain domain (Ericsson & Smith, 1991) and recent proposals about a long-term working memory (Ericsson & Kintsch, 1995) take this into consideration. Nevertheless, WMC is limited and this limitation affects much of human information processing, also design (Bilda & Gero, 2005, 2007). In this thesis I will concentrate on memory search as a major influence for idea generation.

1.4.3 Idea generation in design cognition

Idea generation as a separate theoretical topic has not been particularly popular in design cognition research or in cognitive psychology. The state-of-the-art studies have addressed pragmatic aspects of design IG using experimental methodology (Shah et al., 2000; Shah, Smith, Vargas Hernandez, Gerkens, & Wulan, 2003; Shah, Vargas Hernandez, & Smith, 2003). One important observation about this development is that the ill-structured problem-solving view commonly used to account for design cognition does not appear to be a very fitting model of design IG. Instead some recent theories of IG have been inspired by the creative cognition approach (Finke, Ward, & Smith, 1992) which goes beyond the problem solving view. In this view, creating something new is heavily influenced by previous experiences and acquired knowledge. These parallels from the creativity research literature have opened up possibilities to investigate new topics possibly more important to the design practice than problem-solving studies. For instance, factors such as provocative stimuli, suspended judgment, incubation, or example exposure (Shah, Smith et al., 2003) would not have been very viable in the terms of the traditional problem-solving approach. I consider them further in the section 2.4.

2 Related Research

This chapter introduces philosophy for investigating design and presents previous design studies relevant for understanding design idea generation. I first introduce the principles of conducting empirical design research. This leads to a review of selected studies. The value of these design experiments is eventually evaluated by contrasting them to the theoretical models of idea generation.

2.1 Background for Design Studies

Research on design idea generation rests on theoretical assumptions about what kind of activity design is (see 1.1.2). The next question is what can be and currently is known about design. The goal of this thesis was to examine the information processes underlying design IG. However, these can not be directly observed, unlikely mechanical systems. The research underlying this dissertation has been carried under the assumption that design can be investigated as a kind of 'semi-transparent box' thinking. This means that some psychological processes of design are available to study through behavioral indicators, but their interpretation is theory-laden and some important processes may have only indirect influences and are unobservable. This means that the designer is not just a black box between inputs and outputs, but that the mediation of inputs and outputs is controlled by processes and mechanisms that are partially available for empirical study. Figure 2.1 illustrates this idea:

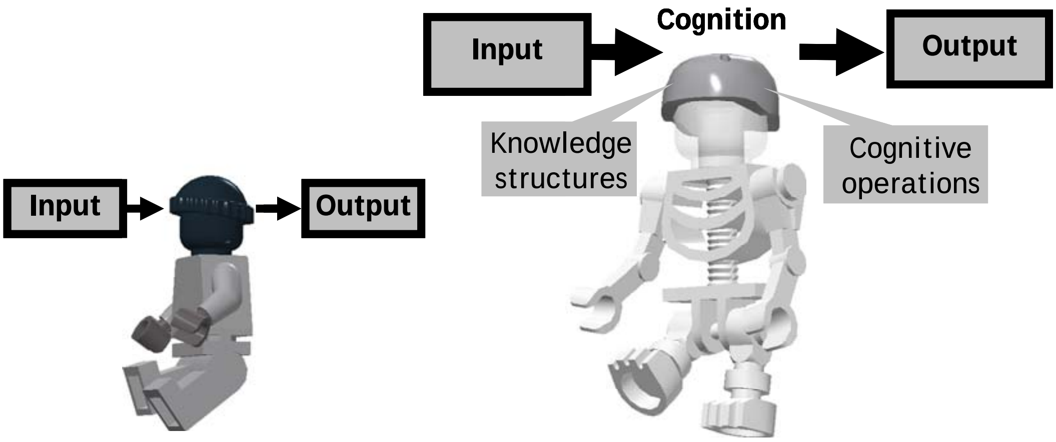

Figure 2.1 Two views of studying design thinking. On left, black box thinking ignores mental structures, emphasizing only the input-output function. On right, semi-transparent model attempts to describe the outputs as a function of cognitive operations on knowledge structures.

The figure displays two types of thinking both relevant for describing design research attitudes. Semi-transparent box thinking assumes certain mental structures and attempts to identify their influence by studying the design output. For instance, these structures may relate to the key concepts of design cognition presented in 1.4.1. This semi-transparent box thinking could be compared to a blend of rational and situated approaches suggested by Fallman (2003; see 1.1.2). The black box thinking ignores these structures, emphasizing only the input-output function. This might correspond to an extreme pragmatic view of design, or Fallman's idea of design practice.

To further illustrate the different attitudes to the study of design, take an example of explaining a hypothetical situation in which certain IG method, say watching Soviet propaganda films, seems to lead to superior performance. Let us consider this from the different perspectives. The pragmatist designer Pete might embrace the black box thinking because it does not matter to him why and how an IG method works, if it produces excellent results. But cognitive scientist Simon might not be satisfied in observing that stimulated brainstorming increases the number of produced ideas twofold. Simon would want to know how the human cognitive processes produce this effect. He would seek a description of design at least as a semi-transparent theory. An optimistic cognitive scientist Oscar might venture further into what might be called 'glass box thinking' and assume that scientific methods can reveal all structures relevant for understanding the effect (cf. rational account Fallman, 2003). Oscar might be already collaborating with cognitive neuroscienstist Nelson who believes that brain research can take us to another level in understanding cognition, including such complex activities as creativity and design – to 'brain-machine thinking' (cf. Howard-Jones et al., 2005).

These same attitudes that I have reflected here to design research context have their counterparts in the cognitive theories framework presented in 1.4.1. Pragmatic Pete might only be concerned about performance, whereas Simon would be interested about semantic and algorithm level explanations. Oscar would investigate design at the level of functional architecture and Nelson observe the biological foundations of design. For instance, can all 'higher' levels of theory be reduced to lower level, ultimately biological or material, descriptions? Or do these higher levels necessarily include emergent properties that can not be captured by a lower level theory because they do not exist on such a level? This is a matter of philosophical debate how these different levels relate to each other and that discussion goes back to a long era of studies in the philosophy of mind considering the relation of mental functions and biological organization (Dennett, 1987; Fodor, 1976). However, in the present context, this discussion about theoretical attitudes will suffice and I will only state that the majority of the related work presented here shares the perspective of Simon. Similarly, my interest is in the algorithm level as defined earlier, not indicating that the theory would be presented as an algorithm.

2.2 Methods for Design Research

Research is necessarily more than just a bunch of theoretical assumptions. The methodology available for the psychological study of design is nowadays considerable. Already Thomas and Carroll (1979) laid out a number of different approaches for investigating design. They grouped design study methods into expert experiments, controlled free-response experiments, and controlled restricted-response experiments. Beyond experiments, case studies and quasi-experiments have emerged since that time as important new methods. For this thesis, I have picked out some of the most essential methods and describe them in the following paragraphs. For instance, ethnographic approaches to design research are omitted here. To get a broader picture of design, read about case studies (Yin, 2003), see Thomas and Carroll (1979), or explore any recent volume of Design Studies to discover the variety of research methods.

2.2.1 Introduction to experimental research

This subsection briefly describes the basics of experimental design research. It is intended to help understanding the results of the reviewed studies and work carried out for this thesis. Design idea generation studies (see, for instance Shah et al., 2000; Shah, Smith et al., 2003; Shah, Vargas Hernandez et al., 2003) are typically experimental psychological (social or cognitive) studies. Experimental research is conducted to determine causal relations; i.e. what consequence do changes in fixed *factors* (*independent variables*) have in terms of certain outcomes (*dependent variables*). This is ideally carried out in a controlled manner so that only certain fixed factor is changed between the conditions and the possible change in outcomes can thus be attributed to the change of factor. In the spirit of semi-transparent box thinking this cause should be explained by referring to the properties of cognition. An example setup of an experimental idea generation study would be to investigate how the group size (independent variable) affects the amount of ideas produced by one person (dependent variable).

Real experiments often employ multiple levels of independent variables. For instance, there can be several group sizes in an IG experiment. Several independent variables can also coexist, so that in addition to group size, same and mixed-sex groups can be compared. As a result, the experimental setup can be described as a formula of the number of different independent levels. The present setup might be called as 3 x 2 design, three indicating the number of different group sizes and two groups compositions (same or mixed). Subjects are assigned to different experimental groups, so that single subject produces data about one level of independent variable (e.g. works only in a 4-person group). This creates a *between-subjects* design. Alternatively the participants can be included in several levels (e.g. work alone and in a group), which is called a *within-subjects* or a *repeated-measures* design.

The results of an experiment are commonly expressed as *main* and *interaction* effects, which are statistically confirmed usually by some analysis of variance procedure (ANOVA, ANCOVA, MANOVA, etc.). If there are differences between levels of a factor, then a main effect is found. If some difference emerges only with a certain combination of levels, e.g. with the biggest group size and same sex groups, then an interaction effect is found.

Experimental research with human participants is challenging to design and implement. Running experiments requires recruitment and organization of subjects. People are seldom alike one another or completely controllable robots. In order to acquire reliable results, the number of measurements must be adequate and then statistically tested. The number of independent factor levels in a between-subjects setup gives the number of required independent groups, each of which should be big enough to filter out individual differences. For instance, a proper 2 x 2 design would required 4 groups to balance the design. When the designs get complex (such as 2 x 2 x 2 x 2 in Shah, Smith et al., 2003), the required number of participants for a completely balanced design increases considerably. Complex designs can also produce interaction effects that can get difficult to interpret. For instance, if we add factors 'visual stimuli' and 'incubation' to the group size and composition, we may end up having a four-factor (four-way) interaction effect. This means that some combination of factor levels together produces an effect that would be invisible otherwise. If it often becomes difficult to explain these effects by a theory, it is better to use more simple design or partial factorial design, which can omit interactions. Of course this means somewhat rejecting the data-grounded truth.

Although several guidelines for experimental research exist, studies on humans are much more difficult to control than field crop in botanical investigations. In practice, social and psychological experiments are somewhat compromised and might be more accurately described as quasi-experimental research (Shadish, Cook, & Campbell, 2002). This refers to the fact that the assignment of individuals to groups may not be truly random and variables that cannot be controlled affect data collection.

2.2.2 Characteristics of idea generation studies

Idea generation experiments have some special features. In practice, experimental research on design IG requires limiting the freedom of designers. In IG studies participants need to follow quite strict orders and adapt working styles that they might not otherwise follow. The fact that only a few factors are manipulated at a time to single out other influences necessarily decreases the similarity of real and experiment-sparked IG. The experimental control is necessary for research but problematic for ecological validity. Thus I tend think that the studies introduced in and conducted for this thesis as *psychological experiments that address design-related questions*, rather than vice versa.

Second, design studies always require designers. In psychology, subjects have been traditionally selected by convenience. The majority of published design studies compare groups of students. This has also been the approach in the constituent studies underlying this dissertation. This is problematic to some extent, as there are known effects of gaining skills and knowledge, expertise in design. (Cross, 2004b; Lawson & Dorst, 2005; McDonnell, Lloyd, & Valkenburg, 2004). However for IG research, the uniform education and lack of 'real' experience might be beneficial (see discussion in Publication II), as it hypothesized to reduce variation in IG results.

For IG studies, it is notable whether people actually work in isolation or as an interactive group. In Brainstorming literature, the concept of nominal groups has been used to refer to comparison (control) group who work alone, but whose efforts are pooled to create a reference score so that the relative merit of group work can be assessed. It is notable that the group as an information-processing unit (De Dreu, Nijstad, & van Knippenberg, 2008) may behave differently than an individual. This is why the majority of evidence in this thesis has been collected from studies which involve analyses at the individual level.

Design IG studies are organized to assess hypotheses operationalized into independent factors. The influence of these factors requires indicators, dependent variables. The most common variable is the number of ideas (sketches, etc.) produced and is labeled quantity, productivity, or just number. Typically only unique, non-repetitive ideas are counted. This simple figure is often complemented by some measure of creativity even though creativity is difficult to define (Mayer, 1999) and to measure. Typically researchers consider either novelty or quality of the idea. Novelty, diversity, or commonality can be operationalized in several ways, but is generally supposed to index how common the idea is. Quality can be addressed as functionality, feasibility, or even usability (Shah, Vargas Hernandez et al., 2003).

2.2.3 Protocol analysis and case studies

Design protocol analysis is an important stream of design cognition research. It is complementary to the experimental research in attempting to investigate directly cognitive processes involved in design thinking, instead of revealing causal relations between variables. Protocol analysis (Ericsson & Simon, 1984) is commonly known by the name 'think-aloud' method (van Someren, Barnard, & Sandberg, 1994). It is founded on the assumption that people can reveal some parts of their cognitive processes by constantly talking aloud while performing the task of interest. In particular, protocol analysis is assumed to reflect the content held active in working memory. Traditionally, protocols have been purely verbal, but the technological advances in the past two decades have made it possible to acquire and transcribe video protocols as well (e.g. in Akin & Lin, 1995). However, these should be distinguished from video-based *design* methods which have different goals.

Talking while thinking is not natural for most of the people, but subjects can usually adopt this way of working provided some practice. Typically subjects receive a simple warm-up task, for instance a puzzle, to get started with the method. Once the subjects become comfortable with talking while working, the protocol for the real task can be recorded. The experimenter may need to prompt the subjects to keep talking, if they start to hesitate during the brief. After the researcher has acquired the protocols, they are transcribed in verbatim. Transcriptions are divided into segments, which may correspond to individual utterances or phrases.

The protocol analysis is intended to be a theory-driven method. The segments of the protocol need to be coded, or categorized, using a theoretical framework. This framework determines what we can find out from the protocols. Multiple, parallel coding schemes can be used if this is justified by the theoretical approach. Take an example, a design protocol of an architect designing a modern villa from a scratch. It might be coded from two perspectives: sources of information consulted and cognitive operations. The former might be easy to categorize into memory, sketches, and catalogues, but the latter clearly requires a theory of what the cognitive operations might be (as an example see Gero & McNeill, 1998). Categorization of the segments is thus crucial to the quality of data and as it is heavily coder dependent, it is a common procedure to use several coders who independently apply the same coding scheme. The agreement of multiple observers is then determined using some statistical method to achieve a measure of inter-rater reliability.

The result of protocol analysis is a sequence of actions found in the protocol. This should reveal patterns in the application of different cognitive operations. The cognitive scientist can then proceed to evaluate how well these patterns match the predictions of the theory. Protocol analysis can also be applied in a data-driven manner, in which the data are used to develop a coding scheme and a cognitive theory of the target activity as well. This is probably a more common approach in design research which has no solid models of cognitive activity to map design activities to (Publication II, but see also Vargas Hernandez, Shah, & Smith, 2007). Protocol analyses are often carried out in a setting that is not experimental, but closer to a case study due to a small number of subjects rendering it impossible to generalize the results. The main reason is that the protocol method is quite labor intensive for the researcher. For example, Ahmed, Wallace, and Blessing (2003) report that the transcription and coding of a protocol took 25 times the recording time. Case-study approach is also supported by the fact that explorative work can proceed with smaller samples than hypothesis-driven (e.g. Ho, 2001).

Other kinds of case studies (Yin, 2003) also hold an important place in design studies. Case studies do not refer to the application of a certain method, but to a type of inquiry in which observations from a limited number of observations are analyzed, usually qualitatively and over an extended period of time, to a considerable detail. The strength of case studies is ecological validity, as they are usually the only method that can be applied in natural environments. For instance, professional architects may be impossible to study in large numbers, particularly in a laboratory environment. Thus the only way to learn from their working is to study a selected few in their real environment as case studies. Their shortcoming is that they lack the power of causal explanation.

2.2.4 Qualitative methods

Qualitative methods can also produce information about IG and design creativity, but on a different level. They are also tools normally used in case studies. For an experimental researcher, they have a supporting role. Instead of addressing factors that influence design thinking they attempt to provide an understanding of design and explore the present state of thinking (e.g. as in Publication V). These methods originate from social sciences and include *surveys*, *questionnaires*, and *interviews*. They can be applied as structured, semi-structured, or open-ended instruments. They provide qualitative information about design and produce data on a level that some may feel to be closer to the reality of design. They can touch phenomena that are difficult to address by experimental, quantitative methodology.

The scope of qualitative methodology is largely determined by what the informants know and are able to tell. The investigators' role in interpreting data is vital. For many activities, including idea generation (Landau, Marsh, & Parsons Iv, 2000; Marsh, Landau, & Hicks, 1997), subjects' insights about how they perform some activity may be very biased. The reliability and the validity of qualitative research are maybe even more critical than in experimental studies. In experimental research, poor research design typically produces null results without challenging the null hypothesis, in qualitative research poor design may produce seemingly important findings that are impossible to explain by any other factor than the poor design itself (e.g. badly formulated forced choice items).

The gap between qualitative and quantitative methods is not necessarily a very clear one. Typically data acquired by questionnaires, for example, are analyzed as if they were quantitative and examined using factorial analysis, uni- or multivariate analysis of variance, multidimensional scaling, correspondence analysis, and so forth. As a consequence, the reported results may closely resemble those of experimental research even though the nature of the research is very different (e.g. in Publication V).

2.3 Phenomena of Design Idea Generation

Experimental research has so far examined a number of independent variables for their influence on design IG. The results of design experimentation could be enumerated as a long list of studies that complement, contradict, or have nothing to do with each other. The approach I favor here is to group the work along research questions, or the phenomena of idea generation. The features I will consider are idea clustering, stimulation, fixation, and time pressure. All these phenomena relate to cognitive processes, in the spirit of semi-transparent box thinking. They have been selected here because they are good examples of what *can* be explained by using cognitive vocabulary.

2.3.1 Clustering and similarity

In an effective design idea generation session, participants are expected produce many ideas in a short period of time. For instance, Kelley (Kelley & Littman, 2005) states that a typical one hour session at IDEO consultancy yields approximately hundred ideas. However, it is very unlikely that all those ideas would be radically different from each other. *Clustering* of ideas refers to the fact that ideas consecutively produced by one individual tend to be similar to each, i.e. are clustered (Nijstad, Stroebe, & Lodewijkx, 2002, 2003). Clusters are usually though of as categories, which in psychology refers to sets of related concepts (Barsalou, 1983; Rosch, 1978), akin to how Wittgenstein defined family resemblance in philosophy (Rosch & Mervis, 1996; Wittgenstein, 1953). The categorical structure is seen as a constituent for human cognition and therefore, for instance, studies of IG attempt to investigate how ideas produced in creative tasks reflect this assumed internal structure.

Clustering is thus an observable, behavioral phenomenon that stems from a psychological structure. Mental categories have so called graded structure which means that the boundaries of the categories are not unequivocal (Barsalou, 1983). This makes it difficult to judge intuitively when the category limits are exceeded. To give an example, is pea a fruit or a vegetable? However, in experimental studies, a large pool of ideas can help to establish categories that independent human judges can agree on. For instance, the definition of categorical fluency in the traditional tests of creative thinking relies on this notion (Torrance, 1974). An interesting, related feature of clustering and functioning of the creative cognition is the clustering of initial ideas across a large pool of people. The *first ideas* are typically quite stereotypic and often shared between members of a group consisting of people from similar backgrounds (Publication II; Finke et al., 1992).

2.3.2 Effects of examples

Stimulation is the 'positive' effect that consulting external material prior to or during idea generation has. Many design practitioners share the view that all sort of external material can help and inspire the production of new designs. With some precautions, this seems to be the case (Coskun, Paulus, Brown, & Sherwood, 2000; Dugosh, Paulus, Roland, & Yang, 2000; Nijstad et al., 2002), although the evidence from product design is scarce (Perttula & Sipilä, 2007). The stimulation is believed to help designers to get started with the ideation process. The stimulation helps mainly to create ideas that are similar to the stimuli, i.e. are from the same or closely related mental categories. For this reason, heterogeneous stimuli presenting multiple categories are preferred and have been found to facilitate the production of more diverse ideas. This is also indirectly supported by findings from basic creativity research, which has examined the introduction of unrelated stimuli or randomly constrained thinking as a helpful factor for creative efforts (Finke et al., 1992; Howard-Jones et al., 2005).

Fixation is the down side of stimulation. It refers to the negative impact of examples. As stated, stimulation helps people by shifting the IG process to a certain direction, which might also be unwanted. A number of studies under the label of 'design fixation' have tried to characterize this process in design (see also Jansson & Smith, 1991; Publication VI; Purcell & Gero, 1996; Purcell, Williams, Gero, & Colbron, 1993). They define design fixation as a tendency to unknowingly reproduce parts of the given examples to independent work. This occurs even if the examples contradict the design requirements. Similar phenomenon is described as unconscious plagiarism in the psychological literature (Chrysikou & Weisberg, 2005; Marsh, Bink, & Hicks, 1999; Marsh, Landau, & Hicks, 1996; Marsh et al., 1997; S. M. Smith, 1995; S. M. Smith, Ward, & Schumacher, 1993). In all, this evidence points out that fixation and stimulation are real phenomena that should not be ignored and can not be easily evaded by simple manipulation of task brief or instruction.

2.3.3 Time effects

There is a lack of research regarding time factors in design idea generation. Many IG experiments employ setups that control time (e.g. time decomposition in Dennis et al., 1999) and thus are connected to the time factors. But because fixed intervals are used, the effect of time remains hidden. Publication IV presented a first step to analyze the time effects encountered in IG and is paraphrased here. Based on research on other areas of idea generation, there are at least three time pressure effects, *incubation, total time for IG,* and *perceived time pressure*. Incubation is a controversial topic that originates from the four-phase process model of creativity formulated by Wallas in early 20th century (quoted in Weisberg, 1986). Wallas argued that the creative process proceeds from problem finding to incubation and eventually to illumination, or insight, followed by verification. Psychologists and design researchers have more recently tried to assess what good does incubation, time off task, do for the problem solving. The main questions have been, does incubation help, and if it does, why?

Wallas thought incubation would be a necessary period of unconscious problem solving preceding insight. In 1980's Weisberg refuted this explanation, claiming that there is no evidence of unconscious problem solving. Regardless of the explanation, several investigations in general psychology (Ellwood, Pallier, Snyder, & Gallate, 2009; Mandler, 1994; Snyder, Mitchell, Ellwood, Yates, & Pallier, 2004), and also in design IG (Shah, Smith, & Vargas Hernandez, 2006), have demonstrated that incubation period does improve IG performance. The recent meta-analysis by Sio and Ormerod (2009) supports this view. As their conclusion, the authors indicate a positive incubation effect particularly for 'divergent thinking' tasks in comparison to visual or linguistic insight tasks. The effect is augmented by a longer duration and decreased cognitive load during the incubation period.

Total time for IG refers to the productivity over a period of time in the context a relatively short, single IG session. Several studies that have followed the course of ideation show that productivity seems to steadily decrease over time, but does not die out completely (Howard-Jones & Murray, 2003; Publication VI; Kelly, Futoran, & McGrath, 1990). Productivity over time is also characterized by an initial peak in productivity, which occurs during the first 3-5 minutes of the IG session. This repeated finding is visualized in Figure 2.2. A study by Snyder, Mitchell, Ellwood, Yates, & Pallier (2004) demonstrated that the initial peak in productivity repeats after a 5 min break, as the notion of incubation would predict.

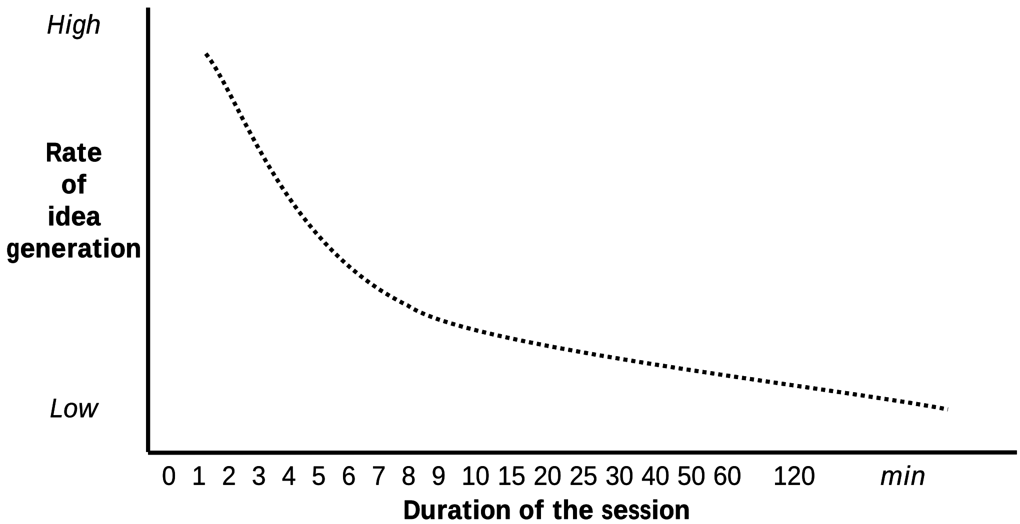

Figure 2.2 Typical rate of idea generation as a function of time when the process is not manipulated during the session. Adapted from Figure 2 of publication IV.

Time pressure is a psychological variable, based on perceived demand and available time. As all phases of the design process must be adjusted to fit organizational time tables, time pressure can influence design on many levels (see Publication IV). Naturally it is particularly visible in low level actions, such as IG, which maybe scheduled for couple hours, after which results are expected. The level of interest here is hence an IG session. Time pressure has been repeatedly suggested to relate to 'creativity' as an inverted U-shape curve (Amabile, 1998; Baer & Oldham, 2006) such as the one displayed in Figure 2.3. This suggests that both too much and too little time can hamper creativity (combined novelty and utility). This is quite logical when it comes to the scarcity of time, as any system exploring a multitude of opportunities with a limited processing rate will necessary resort to shallow processing and respond too quick or with too few opportunities, as a consequence of limited processing time. Top performance at the asymptote of the curve implies that if the time and requirements match with person's self-perceived capability then this can lead to high motivation and superior task performance. The top performance level will very likely resemble a flow experience, which is argued to be associated with high creative output (Csikzentmihalyi, 1996). The right end of the curve apparently reflects a lack of motivation. It should be noted that the obvious problem with this description is that the 'right' time pressure need to be empirically defined for each case (e.g. in Kelly & Karau, 1993).

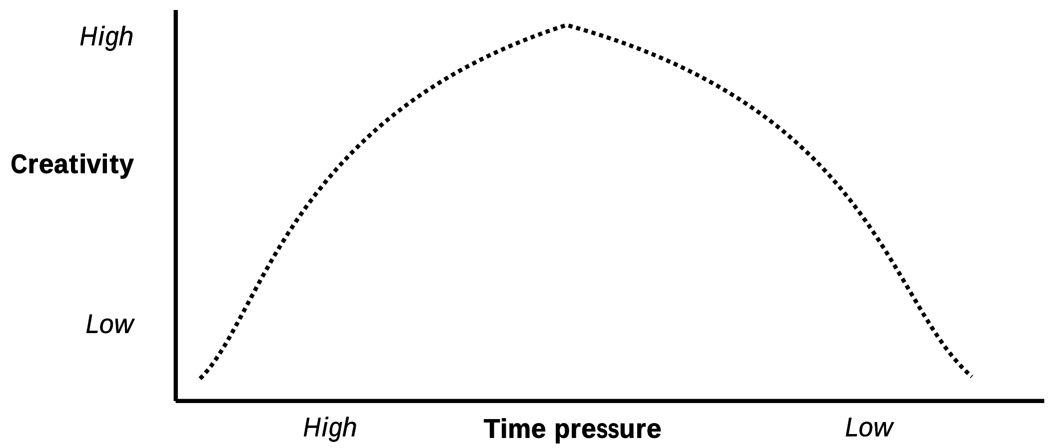

Figure 2.3 Curvilinear relation of creativity and perceived time pressure on a large time scale (e.g. the whole concept generation phase). Adapted from Figure 3 of publication IV.

A common observation is thus that some amount of time pressure can at least temporarily increase productivity and creativity. This can be understood through a cognitive entrainment theory (Kelly et al., 1990; Kelly & Karau, 1993; F. J. M. Reid & Reed, 2000). The entrainment theory is based on the idea that humans have internal, biological rhythms that regulate many bodily functions and influence overt behavior. Another assumption is that these rhythms can be externally adjusted to some extent. For instance, person may compensate for the shortage of time (increased time pressure) by increasing effort. More importantly, this change may sustain for a short period of time even if the task requirements change and the time pressure is lifted. This leads to a hypothesis that if an idea generation session is divided into two parts and the first part has high time pressure, then it will induce an increase in productivity for the second part. This increase will also affect the following session, even if the time pressure disappears.

There is some experimental evidence supporting the cognitive entrainment hypothesis. Kelly and associates (Kelly et al., 1990; Kelly & Karau, 1993) have investigated entrainment in a setup in which three consecutive idea generation rounds with a variable amount of time pressure are compared. The pressure levels were determined empirically by observing how much time pilot participant usually took to complete the task. Their results show that initial high time pressure does increase productivity, but may also inhibit creativity (expert ratings on 7-point scale). Figure 2.4 depicts this relation:

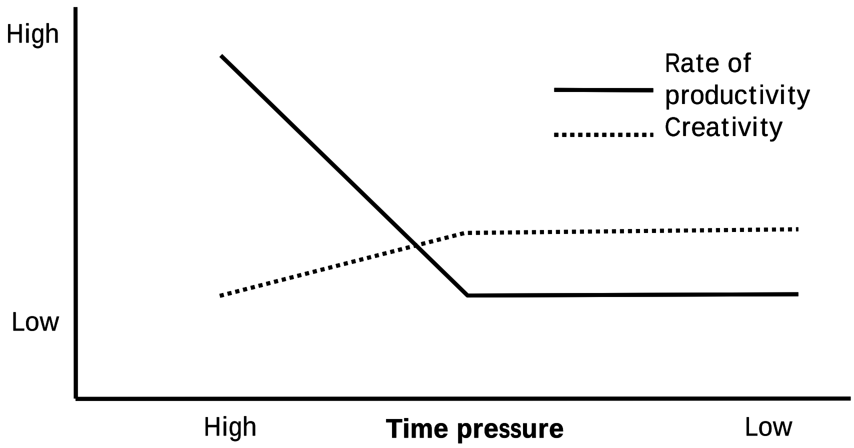

Figure 2.4 Productivity and creativity under different levels of initial time pressure, according to Kelly and associates (Kelly et al., 1990; Kelly & Karau, 1993). Adapted from Figure 4 of publication IV.

However, if after a high pressure IG round more time is given for the following round, the rate of productivity remains high but the creativity of the ideas may also be improved. In a condition where initial time pressure is low but increases towards the last session, the average creativity remains lower (Kelly et al., 1990; Kelly & Karau, 1993). One may notice an evident difference to Figure 2.3 (the absence of leveling creativity under low time pressure), which is probably best understood as a consequence of a very different time line and incommensurable measures of creativity. The low time pressure condition in the studies of Kelly and Karau is not really long enough to decrease motivation for the task. Reid and Reed (2000) have also tested the entrainment hypothesis in an engineering design environment. Instead of applying typical idea-generation research methods, they performed a conversational analysis of the design team interactions. Their results also bespeak of an entrainment effect, cycling between reasoning and communication activities is influenced by the time pressure.

2.4 Models of Idea Generation

As theoretical constructs, models come close to theories but are more complex. In cognitive science, models fall between theories and more extensive cognitive frameworks. Cognitive models can be heuristic, theoretical, or computational. The computational models are the hallmark of cognitive science and further divide into symbolic and connectionist models. Modeling the design IG process is a relatively new initiative. Only in the last couple of years there have been published attempts to present cognitive models of design IG (Publication VII; Vargas Hernandez et al., 2007). This work on design can be seen as an extension to generic IG theories in social psychology and recent advances in creative cognition research.

It is important to note that the models of idea generation should not be equaled with the models of creativity (Sternberg & Lubart, 1999). Those models try to cover a much wider area of human activity and typically the majority of all creative domains. IG models are concentrated in explaining and describing conscious, focused, short-term activity. Where as theories and models of creativity explain high-level creativity, or H-creativity (Boden, 2004), IG models are more concerned with more down to earth, everyday, or personal creativity, if they even should talk about creativity. For instance, the creativity model GenePlore (Finke et al., 1992) is relevant to the topic, but the model is too general and abstract to be introduced here in detail. Similarly, the Concept-Knowledge theory (Hatchuel & Weil, 2009) describes reasoning in design and makes an effort to explain design creativity through expansions of knowledge and concepts. However, it is excluded here because of its generality and non-psychological nature.

Cognitive psychology has a long tradition in modeling various problem solving branches. For example, architectural design has been treated quite well in the past (Akin, 1986). Similarly, for design there are several known frameworks that have been used to describe design activity found in verbal protocols (Akin & Lin, 1995; Dorst, 1995; Gero & McNeill, 1998; Gero & Tang, 2001; Goel & Pirolli, 1992; Purcell & Gero, 1998). However, the idea generation phase of design process has not been particularly emphasized in this tradition as the descriptions have spanned the whole concept development process. This is an important difference because the cognitive operations that are essential in the idea generation phase maybe different from the operations required in other phases of the design process.

If we look for psychological models that address idea generation in particular, we can find two examples from social psychology. These models are *the matrix model* (Brown, Tumeo, Larey, & Paulus, 1998; Coskun et al., 2000) and *SIAM* (Nijstad, 2000; Nijstad & Stroebe, 2006). Their common element is the reference to a data structure, to human memory and its probabilistic sampling, but they embed this mechanism in very different models. They assume that ideas, or their components, already exist in the memory and during idea generation they are retrieved from memory for the construction of new ideas. In addition to these two models, I will introduce Cognitive Network Model of Creativity coming from innovation management domain and Vargas Hernandez Ideation model, which specifically describes design IG. Common in all four is the inclusion of a memory search component. All these models are also focused on individual level, although models about groups as cognitive units and idea generators have just recently emerged (De Dreu et al., 2008). Groups are not in the interest of this study, but their research may prove to be significant for design research as well.

2.4.1 Matrix model

The matrix model (Brown et al., 1998; Coskun et al., 2000) is based on the psychological finding that human memory is organized into categories of information. (Barsalou, 1983; Lakoff, 1986; Rosch, 1978). It is further assumed that ideas are clustered into categories, so that similar bits of knowledge are associated with the same category. In this model, to produce an idea, it must be retrieved from memory. The retrieval is probabilistic, i.e. ideas have different retrieval probabilities, making some common and typical, some rare and novel. The retrieval does not take a chance on retrieving only one idea. Instead, several ideas are consecutively retrieved. The categorical structure of the memory influences the process so that access to one category inhibits succeeding access to other categories. In other words, ideas from the same category are easier to retrieve whereas ideas from a different category are less likely to be retrieved. This is described with category transition probabilities (Brown et al., 1998; Coskun et al., 2000). It should be noted that although this view of memory is inspired by psychological theory, in comparison to the psychological theories of categorization and the structure of cognition, the matrix model is very limited and abstract.

Paulus and his associates have made empirical experiments to evaluate the fit of empirical data to this model. In particular, they have studied clustering of ideas and how the idea generation process matches the cluster structure assumed in the matrix model. Their results indicate that presenting cues throughout the session helps reminding the categories of ideas available to idea generators and clustering predicted by the model does occur (Brown et al., 1998; Coskun et al., 2000).

2.4.2 Search for Ideas in Associative Memory model SIAM

Search for Ideas in Associative Memory (SIAM) IG model has been developed by Nijstad and associates (Nijstad, 2000; Nijstad & Stroebe, 2006). Unlike the matrix model, SIAM does not make detailed assumptions about the human memory structure. The main thesis is simply that the memory is associative – all pieces of information are interconnected. This structure allows for a functionally categorical structure but does not necessitate it. SIAM is more detailed about the process of turning retrieved memory contents into new ideas. The model is composed of two phases, memory retrieval and idea production. Both are detailed in Figure 2.5 below:

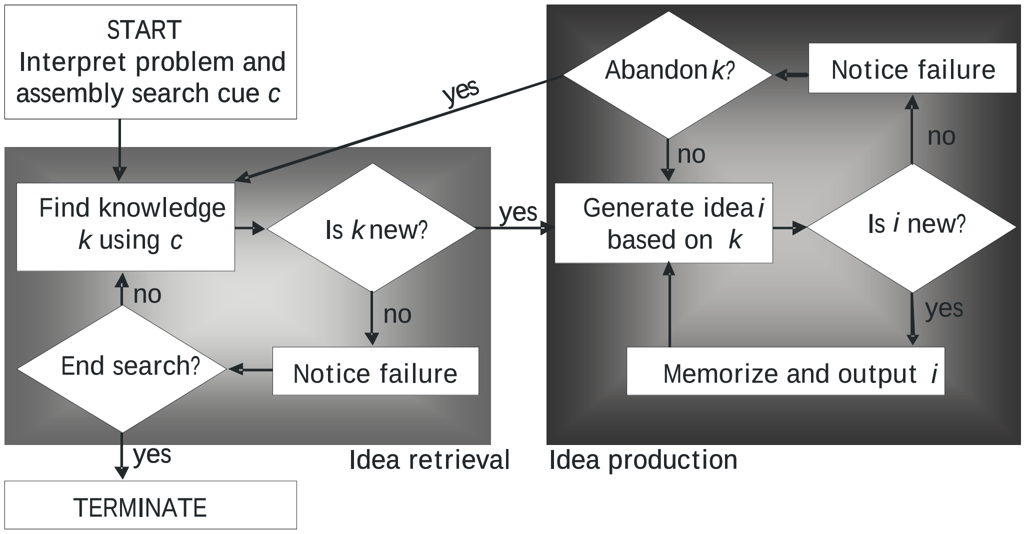

Figure 2.5 Process model of SIAM. The two main phases of idea generation, retrieval (left) and production (right). Adapted from Publication II.

The SIAM model includes some important psychological properties and concepts that are not considered in the matrix model. The differences are evident in the memory retrieval phase, in which *search cue* plays an important role. Cue is necessary in order to be able to access any information from the memory. It is assumed that the associations between cue and bits of knowledge resident in LTM define what can be retrieved from memory. Consider a Google search for 'dog' in which a search term (comparable to the cue) initiates the retrieval and points to 40 million web pages, one sample of all is retrieved at a time by the Internet user (it must be emphasized that Google search is otherwise totally incomparable to SIAM search). Another important feature in the retrieval phase is process control. Sometimes it may turn out impossible to retrieve new information and these errors must be monitored while searching for pieces of knowledge.

Idea production phase of SIAM receives its input from the memory search. This input is called 'images' (Nijstad & Stroebe, 2006) which may be slightly misleading since the input is not required to be pictorial, but rather an image in the sense of speaking more than thousand words, potentially a big chunk of information. It is clearly a larger amount of information than what is accessed in the matrix model and can be used as raw material for producing several ideas. Functionally this resembles clustering of ideas predicted by the matrix model.

In their review paper, Nijstad and Stroebe (2006) consider empirical proof for SIAM. They go through evidence on individual and group level IG. The reviewed studies show two types of clustering, semantic and temporal, both predicted by the model. Semantic clustering was already demonstrated in association to the matrix model evidence. Temporal clustering means that people also produce repetitions from the same category quicker than from other categories. Because the rate of productivity is increases, the total productivity is also higher when clustering occurs, but variety is decreased.

SIAM allows explicating stimulation and fixation effects. Authors also provide evidence that stimulation in IG occurs and can be understood through SIAM as ‘cognitive stimulation’. The stimulation hypothesis is that “*ideas of others, provided that they are attended to, are added to the search cue to activate images in LTM.*” (Nijstad & Stroebe, 2006) This assumption was tested and supported by an empirical study (Nijstad et al., 2002). The number of ideas generated increased with idea exposure more than in a control condition. The quality of the examples also matters. Heterogeneous stimuli selected from multiple categories induces productivity gains in contrast to the homogeneous stimulation and to the control condition. Heterogeneous stimuli also increased the availability of new idea categories, having a positive impact on the variety of produced ideas. Homogeneous stimulation, on one hand, increased the number of ideas per category and thus added to the overall productivity, but on the other hand, decreased the number of ideas in the non-stimulated categories in comparison to the heterogeneous stimulation or control conditions (Nijstad & Stroebe, 2006). This corroborates the view presented in 2.3.2 that the stimuli can have various effects on the IG process.

2.4.3 Cognitive Network Model of Creativity CNMC

The next IG model comes from Santanen, Brigss, and Vreede (2004). Their model is called Cognitive Network Model of Creativity, abbreviated here as CNMC. The model is intended to be predictive in contrast to prominent descriptive accounts of creativity. Even though the authors stress the creativity aspect, CNMC appears to be essentially an IG model. Like SIAM and the matrix model, CNMC is also based on the idea of connected pieces of knowledge, which are called frames. CNMC claims that in idea generation, multiple frames are brought together and creativity arises *“when two or more frames not previously associated with one another are activated together in the context of some new problem.”* (Santanen et al., 2004 p. 176) The process of activating frames is thus essential. It can happen through two paths: by external stimuli activating certain frames or through activation spreading in the LTM networks. Activated frames become available to working memory and can be combined to produce new ideas, as shown in Figure 2.6 on the following page:

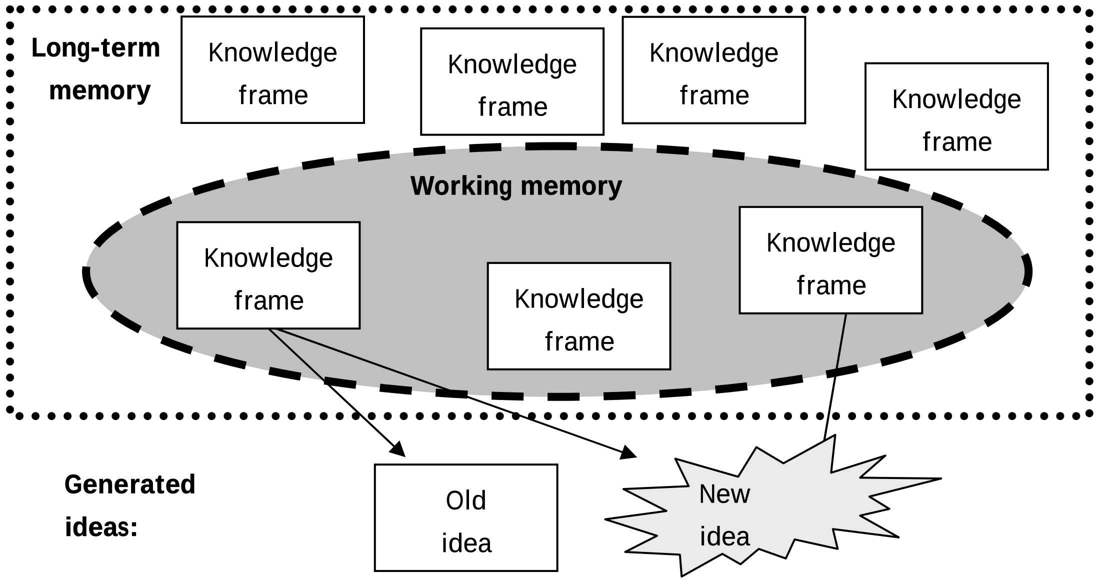

Figure 2.6 Illustration of idea production in the Cognitive Network Model of Creativity based on Santanen et alia (2004). New idea (bottom right) is produced by combining frames active in working memory to form a new idea.

The creative process is restricted by the capacity of working memory. Working memory can only hold some frames active at a time. This means that to produce a good idea, the right frames need to be activated simultaneously. This leads to the predictive part of CNMC. If too many external influences are introduced too rapidly, none of them can be properly attended to. Properties of long-term memory may also constrain creativity because activation may not spread enough in order to activate and bring together disparate frames. This will also prevent the generation of creative ideas. (Santanen et al., 2004)

If the CNMC model is analyzed or compared to the other models, it is clear that the specification is not very detailed. It remains unclear how ideas are really produced, how long-term memory is actually organized, how frames are accessed, or even what they are. However, authors do provide some experimental evidence to test the predictions they derive from CNMC (Santanen et al., 2004). They address two research questions: how external stimuli delivered at a constant rate affect IG and how does stimuli topic switching (cf. heterogeneous stimuli in 2.4.2) affect creativity? Their study evaluated how different temporal patterns of stimulation affected idea production by changing IG topics on different intervals using prompts. The finding was that topic changes occurring every 4 minutes did not affect IG in comparison to a session without prompts. However, groups that had a change every 2 or 8 minutes had mutually similar, high levels of creativity, but in greater numbers in the 8 minute condition.

2.4.4 Vargas Hernandez Ideation Model VHIM

The final idea generation model to be presented here comes from Vargas Hernandez, Shah, and Smith (2007). This contribution is here called the Vargas Hernandez Ideation Model, or VHIM. This proposal might be better called a framework as they present a very complex theory about cognitive mechanisms required for design IG. VHIM is actually a composition of several model variants each intended to explain specific phenomena occurring during idea generation. The structure of VHIM begins from a schema that includes the basic elements for distinct ideation component models. This structure is visualized in Figure 2.7 below.

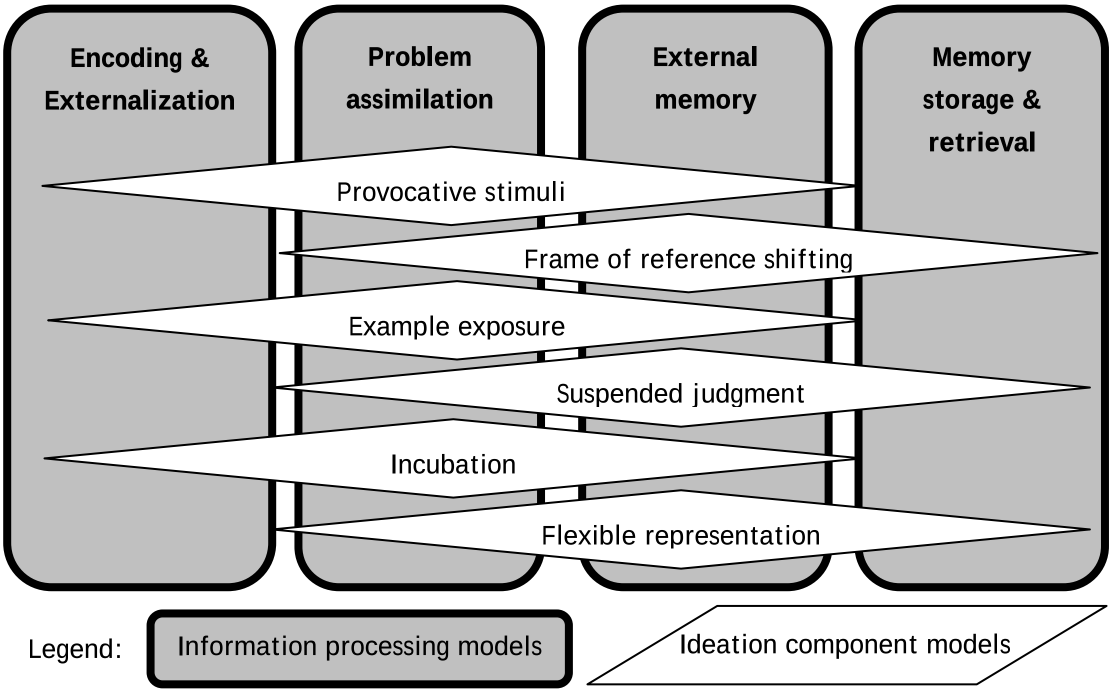

Figure 2.7 Main schema of VHIM consisting of four basic information processing components (vertical boxes) utilized by six different ideation component models (horizontal). In the figure, the component models are illustrative, they are not aligned according to the basic components (not informative).

The schema includes several basic components, or elements, that correspond to basic psychological functions. As parts of the schema, the authors include separate models for basic components including *encoding and externalization process*, *memory storage*, *memory retrieval*, *external memory*, and *problem assimilation*. The models rely on different cognitive constructs, derived mainly from the human information processing framework (Newell & Simon, 1972), but also including features from more recent cognitive theories. The schema also makes a distinction between WM and LTM. The authors introduce two interfaces, called lines that separate external environment from the environment (biological line) and the LTM capacity from working memory capacity (knowledge line). As an example, the basic component for memory retrieval is presented in Figure 2.8. It includes three main functions, recognition, search, and check. These are aligned with the biological and the knowledge line.

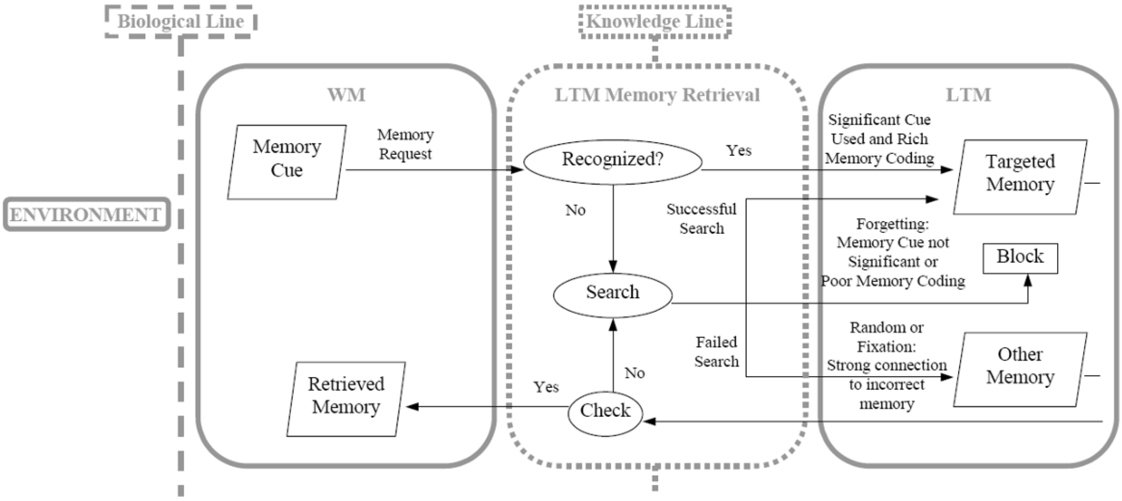

Figure 2.8 Memory search component of VHIM. Figure 4 of Vargas Hernandez, Shah, and Smith (2007) ©ASME international, reprinted with permission

After the cognitive framework for VHIM has been laid out, the authors proceed to apply and modify it to the design ideation context. They present a set of cognitive models of ideation components addressing effects of *incubation*, *example exposure*, *provocative stimuli*, *frame of reference shifting*, *suspended judgment*, and *flexible representation*. These six models are adaptations of the basic component models with some additional mechanisms to account for the particular ideation component.

For instance, the example exposure model (see Figure 2.9, the next page) extends problem assimilation component. It specifies that examples need to be abstracted immediately following the internal representation. The extracted abstract features are used as cues for analogical comparison to retrieve ideas from LTM. After this step, the idea production proceeds according to the basic model of problem assimilation. Similar modifications are included in all component models. For details about the schema, the basic models, and ideation component models see Vargas Hernandez et al. (2007).

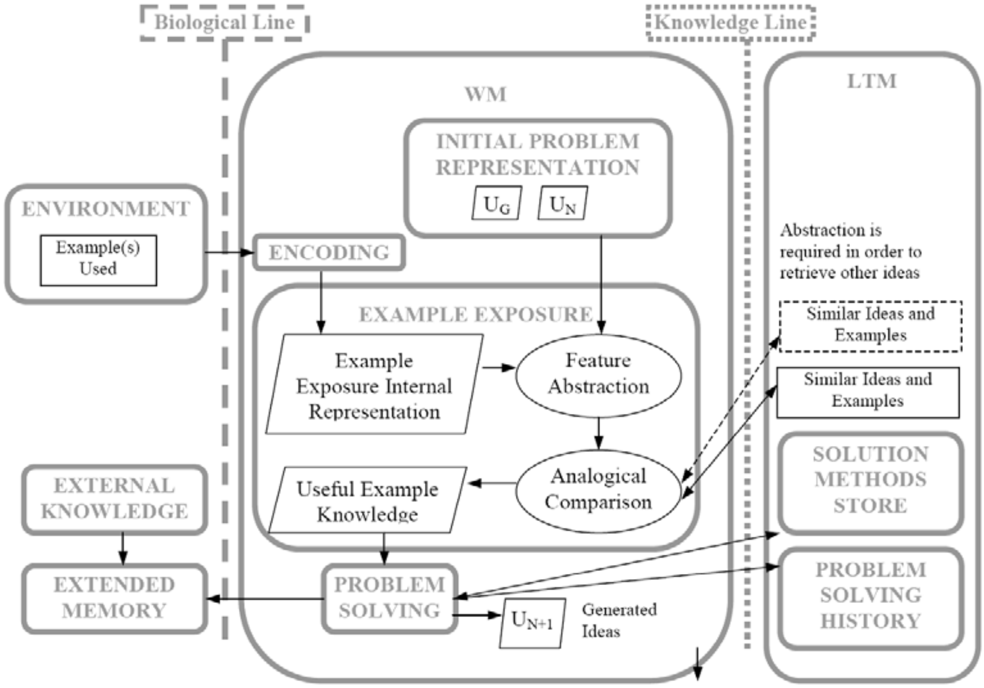

Figure 2.9 Ideation component model for example exposure. Figure 2 of Vargas Hernandez, Shah, and Smith (2007) ©ASME international, reprinted with permission

Along with the model, the authors also discuss how empirical data they have previously acquired fits the model. It must be acknowledged that the authors have built VHIM after a substantial empirical work (Shah et al., 2000; Shah, Smith et al., 2003; Shah, Vargas Hernandez et al., 2003) which implies that it should have a good bottom-up fit. The introduction of separate IG component models clearly shows this development. As an example, the authors illustrate the frame of reference shifting model in accounting for some previous data (Shah et al., 2006). They state that "*designer departs from the original problem to solve an alternative problem with different constraints. … When returning to the original problem solving, the alternate solutions provide inspiration for novel approaches, but the quality of these ideas suffers since it solves a different problem*." This is used to explain the observation why the usefulness of ideas evoked by frame of reference shifting decreases.

Due to the huge scope of VHIM, it is fairly vulnerable to criticism. It evidently aims very high and tries deal with issues that are not yet fully comprehended even within the founding disciplines. In particular, the psychological plausibility of the assumptions and mechanisms proposed within the model is questionable on some instances, for instance the structure and mechanisms of working memory, and the concept extended LTM are debatable. However, the value of VHIM lies in proposing a host of theoretical ideas that could help understanding the phenomena of design IG in a *heuristic* way, rather than thoroughly explaining design IG.

3 Theory of Design Idea Generation Process

> "*We should be aware of why there is reluctance to try to make design processes explicit. Because processes and product are highly intermixed, making explicit ones process gives away some of their design secrets. Others may be able to replicate their designs by replicating their process. Or even more critically, the process may be analyzed and criticized.*"
> (Eastman, 1999)

The previous chapter presented four idea generation models, so is their a need for a new theory? How could a new proposal advance the state of the art embedded in existing theories? I believe that from design perspective, it might be useful to have a model that considers the specifics of design and associates this with the best psychological precision available. In this chapter I will try to make progress towards this end. I present the main contribution of this thesis, a cognitive theory of idea generation in conceptual design, called Model-L. This contribution is primarily theoretical and presents an adaptation of SIAM model to conceptual design context. It extends this reference model on two parts: connecting it to macro level activities required for design IG and on a micro level by specifying new memory-based constraints for the idea production process. The model is intended to be comprehensive on the macro level, but constrained on the micro level. In other words, it should generally fit the majority of design IG activities but not describe all constituent cognitive processes in great detail.

The general goal of Model-L is to facilitate understanding why certain IG practices can lead to certain consequences. For this dissertation, Model-L is a summary and synthesis of the line studies initiated in Publication VII, and continued in Publications III, I, and II, indirectly supported by IV, V, and VI (see 3.2). Some new contributions also surface when the model is applied to the analysis of design IG methods and phenomena. The style of presentation here is compact as I attempt to loosely follow a psychological reporting style in laying out the model. This makes the model dependent on the referenced explanatory concepts and I have explicated some of these dependencies in subsection 3.1.1.

As argued in Publications I and II, idea generation in conceptual design can be characterized as information processing in which external task environment and human cognition interact. In the following section, I describe the theory of design IG by introducing the cognitive process and knowledge structures required to achieve this functionality on an abstract, heuristic level. The model is focused on describing the macro level of design IG and the basic memory mechanisms on micro level, rather than trying to provide a comprehensive account of all information processing that can be involved with design IG. The model relies strongly on the assumption that IG is based on the ability to access long-term memory and efficiently retrieve diverse ingredients from it, and to exploit these ingredients in a process of producing new ideas.

In Model-L, the intention is to describe the memory-search part of IG more accurately than in previous models, SIAM or VHIM. In comparison to VHIM, it references the latest psychological literature and it is more focused on few, elaborated cognitive processes and. This means that it considers a subset of design activities. For instance, the expertise model of product design by Kruger and Cross (2006) includes eight steps, *Gather data*, *Assess value and validity of data*, *Identify constraints and requirements*, *Model behaviour and environment*, *Define problems and possibilities*, *Generate partial solutions*, *Evaluate solutions*, and *Assemble a coherent solution*. Compared to this, Model-L is concerned with only two steps, problem definition and the generation of partial solutions. The model is presented as a composition of cognitive *processes* and *knowledge* (or processed information), with the emphasis on combining processes (problem structuring and memory search), which have been described in the constituent publications.

3.1 Model-L of Design Idea Generation

Model-L is intended to be a *descriptive* psychological account of IG in design. It attempts to describe psychologically what occurs during design IG. This is a crucial difference to the prescriptive models of design introduced by Cross (1984), Pahl & Beitz (2007), or Ulrich and Eppinger (2008) that advice how one should carry out design tasks. The prescriptive models need to be close to the design practice, where as prescriptive, psychological models may constrain themselves to a detailed analysis of some very small portion of the whole design process.

In Model-L the idea generation activity is modeled using a four-step macro-level model and with a micro-level components which, for example, describe memory-based IG in detail. The outline of the macro-level process was presented in Publication VII. This framework discussed requirements for generating ideas by accessing LTM contents and was the first attempt to apply SIAM to a conceptual design context. The proposal was called cue-based memory probing in idea generation (CuPRIG) at the time being (Publication VII). This notion of memory search was further developed and clarified in Publication II for the micro-level model and is here coupled with the macro-level model introduced in Publication I.

3.1.1 Background assumptions

The presented theory rests of a number of premises, which are adopted from the psychological and design literature. The model introduced here puts together several pieces of the theory, some which are transferred beyond their original context. This means that much of the credibility of the model relies on the cross-domain applicability of the introduced concepts. I present tests of few of the presented concepts in the section 3.2 Empirical Evidence and discuss the domain independency assumption in 4.3.

The main assumption in this thesis is that IG is largely about memory retrieval and knowledge reuse. This is generally accepted notion, although its exact formulation differs among writers, consider for instance the idea-generation models presented earlier, the GenePlore model for creativity (Finke et al., 1992), and the views of creativity and expertise (Klahr & Simon, 1999; Weisberg, 1999). The metaphor used here to characterize the function of memory is *free recall* (Nijstad, 2000; Raaijmakers & Shiffrin, 1981). This psychological construct is assumed to be comparable to idea generation. It must be noted that free recall in psychology refers to a task in which people are requested to remember items from a list presented to them some time ago. This means that the goals of idea generation and free recall are somewhat different operations. Memory search might also be compared to the concepts of cued-recall or ad hoc category formation (Barsalou, 1983), but I here remain true to the free recall metaphor. An important property of the search is its probabilistic nature. The cue-overload principle states that there are usually multiple memories associated with any memory cue (Baddeley et al., 2009). This indicates that the retrieval attempt creates a kind of competition, i.e. becomes probabilistic, which suits idea generation very well, allowing one set of cues to retrieve a number of different memories for idea production (cf. SIAM in 2.5).

Another major assumption is that the memory-search view can somehow be connected to traditional problem-solving models (see Goel & Pirolli, 1992; Simon, 1973). This has not been explicitly presented before and therefore poses some additional questions about the validity of this approach. One part of the problem-solving process, problem interpretation is considered as one of the main components of Model-L. However, the evidence and studies regarding design, or ill-structured, problem interpretation are very scarce. The development of the topic in Publication I already presents some previously unvoiced ideas, particularly on the role of interpretation and implicit decomposition (see the following subsection), but for the most part these ideas remain to be tested.

3.1.2 Process

The first thing required by the IG process is a macro-level control over the activity. The designer must have some means of control in attending to a design task to proceed with IG (Publication I). In response to the task, the designer produces ideas, descriptions of devices satisfying the problem description. In Model-L idea generation is considered as an *iterative problem-solving* or *satisfaction* process which happens on interpreted, *decomposed* subproblems. In concordance with the prescriptive literature (Cross, 2008; Pahl et al., 2007; Ulrich & Eppinger, 2008) and traditional problem solving theories (Egan & Greeno, 1974; Laird, Rosenbloom, & Newell, 1986; Newell & Simon, 1972), it is assumed that designer mentally constructs the design problem as a combination of multiple features. This idea matches with the problem analysis in the prescriptive models of the design methodology thinking by Alexander, Jones, and Archer (Alexander, 1963; Archer, 1965; Jones, 1963). In addition to decomposition, this procedure is also called subgoaling, problem structuring, or partitioning. The macro-level model is illustrated in Figure 3.1 below:

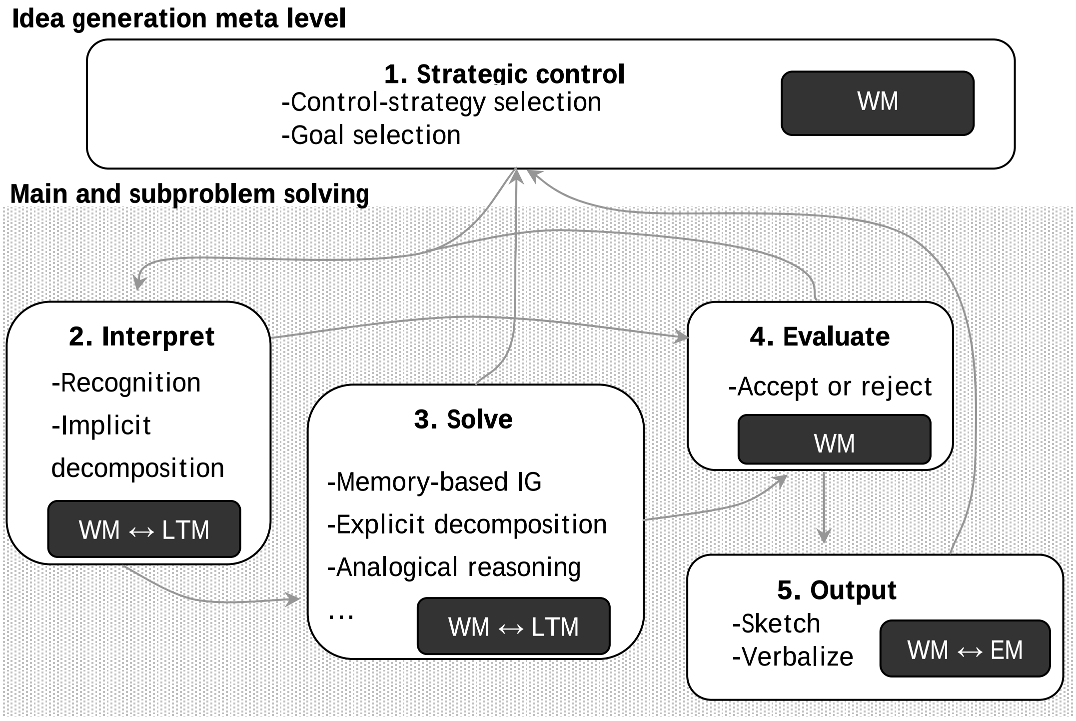

Figure 3.1 Macro-level model of design IG of Model-L. Model consists of four problem solving stages with different memory requirements. Black WM, LTM, and EM boxes indicate the shifting of emphasis between working memory, long-term memory, WM-LTM interaction or WM-EM interaction. Modified from Publication I.

On the top level (stage 1 in the figure), the model includes strategies to control the processing of different subgoals. Note that in this iterative development, subgoals are for the first time extracted in the second stage. Control strategies come close to Akin's (1986) global search methods. Strategies regulate how subgoals are attended to during IG. Control strategies are usually classified into breadth-first and depth-first, reflecting the order and the level of abstraction in subgoal processing (Ball & Ormerod, 1995). Both can be labelled as structured, top-down problem-solving approaches. The breadth-first strategy requires that each subproblem is solved at a certain level of detail before getting into more detail, whereas the depth-first strategy means that each subgoal is independently solved to a considerable level of detail before attending to the next subgoal. Sometimes these modes unite in apparently opportunistic designs (Ball & Ormerod, 1995). Strategic control is assumable a very general, domain-independent mechanism used with many types of problems, not just with ill-structured ones.

At the beginning of the problem-solving process designer must *interpret* the problem (stage 2 in Figure 3.1), that is, produce its mental representation. This representation comes close to what has traditionally been called problem space, although it is unlikely that the mental representation can include but a tiny part of potential space, in particular when dealing with ill-structured design problems. Interpretation, alike the following problem solving stages, is applicable on all problem-solving levels, iteratively from the main problem to various subgoal levels, producing nested, hierarchical problem spaces. According to Federico (1995), the interpretation of an ill-structured problem happens by matching the problem description by its surface-level features with the existing solution models in LTM. In other words, by comparing it to known problems or solutions.

In Model-L, two important cognitive actions are involved in the interpretation process: **recognition** and **implicit decomposition**. It is essential that both activities are automatic and largely out of conscious control. *Recognition* is a strong problem-solving method that can lead to the immediate discovery of a solution. It is usually described as a spontaneous (implicit) and effortless activity, characteristic of expert performance, and dependent on domain knowledge (Gobet & Simon, 1998; Lawson, 2004; Stein, 2004). The chances of successfully applying recognition increase as the surface-level similarity between the current problem and known solutions increases. If the current problem and the known models match poorly, then the interpretation process may be extended by analogical reasoning mechanisms, which allow transferring knowledge across domains based on conceptual (morphological) similarities (Klahr & Simon, 1999). Analogical mapping is assumed to be cognitively more demanding and is treated with the problem-solving operations of stage 3. However, this assumption should be tested in future, as analogical thinking in brief interpretation has not been studied this far.

In the current model, recognition is intimately coupled with *implicit decomposition*. When task-relevant knowledge is retrieved during a recognition attempt, it seems possible to use the recovered knowledge to deduce a function structure (subgoals) of the solution, that is to effectively decompose the problem. This implies a difference between experts and novices in problem decomposition because experts can recognise and recall more complex solutions owing to their huge knowledge base, organized in bigger chunks (Akin, 1986). For the same reason, experts might be able to find an alternative function structure later on by restarting decomposition process explicitly (stage 3 in Figure 3.1). In contrast, novice designers may only retrieve incomplete or unfit matches that still provide enough information for implicit decomposition. Similar expertise effect on analytical skills has been observed, for instance, in classifying physics problems (Chi, Feltovich, & Glaser, 1981).

If interpretation does not provide a direct solution via recognition, it is still expected to provide some kind of a problem structure through implicit decomposition. This should correspond to understanding 'what this design task is about.' The existence of a problem structure allows the designer to start **solving** individual subproblems (stage 3 in Figure 3.1). The search begins with the selection of the most highly prioritized subgoal (Laird et al., 1986). Assuming that the solution cannot be achieved by recognition, the solution must be sought using a variety of other problem-solving methods. These include, but are not limited to, **memory-based mechanisms**, **explicit decomposition**, and heuristics of IG (see Akin 1986; Klahr and Simon, 1999). This is described in detail in the following paragraphs, which demonstrate how memory search and idea production together can generate ideas.

Explicit decomposition refers to the discovery of a subproblem structure. Decomposition at a lower abstraction level must be preceded by higher level decomposition (implicit or explicit), because we can not expect the designer to decompose an unknown subproblem, or to satisfy an unknown requirement. This also justifies the restriction presented in the educational literature that decomposition should precede IG. On the other hand, explicit decomposition may be completely skipped if there are no matching solutions (no templates), or if several recognizable solutions are available. In the former case, decomposition is impossible, in the latter, it is unnecessary for problem solving.

Memory search is likely the most important source for ideas of across domains, including design. In publication II, it was argued that SIAM model (see 2.4.2) provides a good starting point for conceptualizing this process, also because it is based on a psychological, tested memory model Search of associative memory (Raaijmakers & Shiffrin, 1981). However, several shortcomings were also noted. Difficulties relate mostly to the fact that the psychological memory theories describe experimental data from basic research settings. These experiments often have very different goals from IG. Thus some additions that would make SIAM more realistic were proposed in Publication II. Specifically, **context sensitivity** and a **limited working memory capacity** are important properties of human memory that will be considered.

Context sensitivity is an essential feature of human memory. It involves both encoding and retrieval of memories. It is important to distinguish what is meant by context, as several definitions exist. I use the term context to refer to primarily physical, spatial setting, an environment. This matches, for instance, Baddeley's (1982) definition of independent context in which meaning is independent of the context. The function of context provides a way to organize human memory. The dependency of human memory on physical context facilitates everyday functions by allowing us to more easily recall facts relevant to a certain environment when we are there. This enables habituation to patterns that we repeatedly perform during our daily routines, such as making breakfast, turning off lights, or flushing the toilet (see Wood & Neal, 2007). However, this has the downside that recalling information about remote contexts, such as the condition of your kitchen or bathroom while shopping in a supermarket, will be more difficult because of the missing contextual cues.

The argument presented in Publication II is that neglecting context is a major problem for present memory-based models of IG. The context dependency is an equally big concern for design IG practices. Although no exact statistics exist to my best knowledge, it is very likely that the majority of design IG takes places within the protective walls of a R&D department. How many companies are actually producing products and services for office environment? If the current proposal is on the right track, then one could expect clear benefits for IG to be gained if the process was transferred to the intended context of use. This is because the contextual change facilitates the access to the relevant body of knowledge, making it more readily available for the designer.

Context sensitivity is related to the search cues, as they are together believed to determine the possibilities of the memory-search process. But what exactly are the search cues in memory-based IG process? This is a tough question as even psychologists building the memory-search models have been reluctant to provide any detailed accounts of cues on the algorithmic level (Kahana, 1996; Unsworth & Engle, 2007). As argued in Publications VII, III, and II, the algorithmic level beyond the superficial level of language (cf. Chomsky, 1957) is *non-trivially* related to the semantic features of the design brief (e.g. linguistic and pictorial information) and available information. This means that the externally received cues maybe processed further and it impossible to know how they are actually filtered for the memory search (see Harfield, 2007). We tested the cue-based search mechanisms in Publications II and III and showed how the process at large is sensitive to semantic cues. In our case, we inferred that the provided keywords ('water' or 'sun') had affected memory search by observing a change in the quality of produced ideas.

Working memory capacity is another crucial concept in cognitive psychology. It is commonly applied to explain various features of mental performance as it provides a major limitation for human performance. However, the utilization of WMC is not very straightforward for several reasons. The confusions about the construct were already mentioned in Introduction (section 1.4.2), which implies that the concept WMC might be difficult to apply. Hence, it is not surprising that WMC has been somewhat over looked attribute in IG models, expect for CNMC model (see 2.4.3). I believe that the WMC limitations have multiple consequences for IG which should and partially can be enumerated. This work thus needs to make a stance on WMC. Relying on what Unsworth and Engle have recently suggested in the psychological literature (Unsworth & Engle, 2007), I assume that working memory is best described as an activated part of the LTM, or as a temporary view into LTM. Importantly, WM is not a storage in which information from LTM would be temporarily stored in. Instead it is a mechanism that allows retrieving information from LTM by performing search operations that can open up access into different LTM contents. This feels natural as it consolidates the position of search as a central piece in the puzzle.

Furthermore, Unsworth and Engle argue that there are individual differences in WMC. These show in difficulties in focusing the memory search that is low WMC individuals are in a greater risk of losing the track of relevant information with regards to the goal of the recall task. However, they also posit that low WMC individuals exhibit lower performance in psychological memory tests because they associate cues with a larger number of items than high WMC individuals. It is not clear what this implicates for creative tasks, such as design, if they are considered to comparable to free recall. However, the lack of goal-relevance might discriminate between low and high WMC individuals' IG capacity if we believe that high WMC should exhibit higher creative output as well (for indirect evidence about this relation see Gilhooly & Murphy, 2005; Rosen & Engle, 1997). The errors may arise from the difficulties in retrieving new task-relevant knowledge. It is thus hypothesized that when a person says that they can not come up with anything new, they are likely having problems with finding the right information. They are stuck retrieving only memories perceived irrelevant and which can not be included for idea production.

Memory search by itself is not enough to produce any new ideas if we assume that the retrieved memory contents can not very extraordinary. Therefore a separate *idea production* mechanism is needed. Idea production phase was not extensively elaborated in the formulations of SIAM (Nijstad, 2000; Nijstad & Stroebe, 2006). This was noted by the authors and in Publication II. Gladly, the literature on creative thinking includes a plenty of proposals on how to address this gap. Nijstad and Stroebe mention creativity templates (Goldenberg, Mazursky, & Solomon, 1999) and similar simple operations of knowledge transformation could be extracted from TRIZ creative problem-solving methodology (Altshuller & Shulyak, 1999), or from the IG heuristics presented by Osborn (Osborn, 1957) . This would be an instance of fairly simple associative thinking in which two or more ordinary concepts are combined to produce a novel idea. For instance, one could associate a cactus and a gun to produce a novel spiked weapon. There are already detailed computational theories of how this kind of conceptual blends or conceptual combinations might be achieved by human cognition. They rely on formalized knowledge and have been implemented computationally to produce novel or even ideas (for instance, see Binsted, 1996; Costello & Keane, 2000).

In sum, the memory-based idea production as a separate micro-level module in Model-L is an extended version of SIAM. No separate flowchart was presented, as the modifications to the SIAM model visualized in Figure 2.5 were small on the process level even if theoretically important.

Analogical reasoning presents a complex mechanism for producing ideas that are creative and not trivially produced from the knowledge stored in memory (Holyoak & Thagard, 1989; Hummel & Holyoak, 1997; Thagard, Holyoak, Nelson, & Gochfeld, 1990). Theories of analogical access and mapping start from formally modelled knowledge representations. By considering the structure of knowledge rather than its surface properties, analogical reasoning can transfer deep structural properties from one knowledge domain to another. It must be mentioned that the basic memory-search mechanisms introduced before are also compulsory for analogical reasoning as the knowledge structures needed for the mapping must be first retrieved from LTM. As these theories do not contradict or complement the assumptions of the memory-search model proposed earlier, the reader is advised to consult the references above.

Having now introduced some processes that can be used to create ideas on the micro level, it is time to return to the macro level of idea generation. Eventually all generated solutions must be evaluated for their compatibility with the problem in question (stage 4 in Figure 3.1). Stopping rules determine what will acceptable as a solution. They should include requirements and properties derived from the task brief and from designer's own style of working (Harfield, 2007), and be influenced by the previously generated ideas. Only if the solution satisfies the stopping rules (Goel & Pirolli, 1992), it will be produced on paper. As an example of the stopping rules, designers seeking novel ideas can intentionally discard a solution for being too ordinary or trivial. This should be especially important when dealing with recognized solutions that are by definition routine answers. If the idea qualifies, then the cycle ends to the output of that idea (stage 5 in Figure 3.1). This application of stopping rules controls the iteration of the IG process. Due to WMC limitations, it may be necessary to document each subsolution after its generation (Bilda & Gero, 2007). For this reason, an additional recomposition procedure seems neither necessary nor feasible in IG as the complete solution is always a combination of solutions, generated in a serial order after resolving all interdependencies in a linear fashion, although some have argued otherwise (Ho, 2001; see also Kruger & Cross, 2006).

3.1.3 Knowledge

The nature of design knowledge is poorly understood. This is a serious limitation for any theory that attempts to present memory-based arguments of design action and also restricts the precision that can be achieved in the present thesis. For present purposes it is assumed that the memory organization is associative (Raaijmakers & Shiffrin, 1981), categorically (Lakoff, 1986; Rosch, 1978) and contextually (Baddeley, 1982; Unsworth & Engle, 2007) organized. It is known for certain that increasing and refining knowledge is a key part in gaining design expertise (Cross, 2004b; Lawson, 2004; Lawson & Dorst, 2005), but the actual outcomes, contents of the expert designers' memory are not really understood. There are few proposals that make claims about the organization of the design knowledge. For instance Gero (1990) discusses 'prototypes' as an information representation schema for design knowledge.

Recently Kurtoglu, Campbell, and Linsey (2009) have introduced a computational conceptual design tool, which includes an implementation of design knowledge representation. Their model is intended to assist human designers in early conceptual design and idea generation. It combines function-based structure synthesis with a graph grammar language to produce functions graphs. The graphs are generated automatically by a synthesis algorithm to help in IG. The representation model includes functions, components, and their configurations. However beyond this and Gero's proposal, there are apparently no interesting implementations of design knowledge representations, at least with regards to design cognition.

3.2 Empirical Evidence

The Model-L was constructed to answer the main question of thesis, i.e. how are design ideas produced, and also to further explicate results from the experiments reported in Publications I and II. It includes evidence from the constituent publications of this dissertation. The pieces of proof relevant for Model-L in each publication have been enumerated on a coarse level in the Table 3.1 on the next page. The publications, I, II, and VI contain more empirical data and are analyzed in devoted paragraphs after the table.

Table 3.1 The relevance of each empirical, constituent publication for Model-L.

Publication	Evidence
I	Associates implicit decomposition with problem interpretation and dissociates explicit decomposition from it. Research subjects systematically apply top-down control strategies, supporting the macro level of Model-L.
II	Study explicates the effects of contextual cueing and verbal stimuli in terms of the memory search model embedded on the micro level of Model-L. Contextual defaulting points out the role of implicit constraints inherent for each designer.
III	Demonstrates the overlap of initial ideas between independent designers with similar education and cultural background. Initial analysis of context and stimulation effects.
IV	Disclose the existence of time-related features of design idea generation. Assembles data showing compatible with the memory-based idea generation model, particularly the initial boost of productivity.
V	Brings evidence of the implicit nature of idea-generation processes and the need to help designer students to adopt useful practices for creative work.
VI	Releases new data relevant for understanding cognitive stimulation through the variability and timing of stimuli, latter utilized in Publication IV. Shows how the stimuli have different potency at various stages of the process.

In the first publication, I analyzed 16 senior students of mechanical engineering working on two design idea generation tasks. In the conducted verbal protocol analysis, I focused on primarily on problem decomposition and the patterns of problem solving. First, through inference two implicit activities of design IG were discovered that had not previously been considered together: recognition and implicit decomposition. It was found that the students used top-down control strategies and quite systematic approaches to generate product concept ideas. The most important finding was that in these conceptual design tasks, analytical methods such as explicit decomposition were generally playing a minor role and did not seem add any value to the IG process.

The empirical study reported Publication III and re-analyzed for Publication II addressed the effect of contextual information and verbal stimuli in design IG. We analyzed conceptual design sketches from IG task committed by 50 engineering students. The analysis showed that contextual information had an important role in guiding the memory search. The data revealed that people commonly make assumptions and introduce implicit and unconscious constraints which was described as **contextual defaulting**. This means that even though designers would in principle be free to select any context, they make predictable assumptions about the context for IG. For instance, in the study presented in Publication II we gave the students a task of designing a ball transportation device for a game. The majority of the subjects interpreted the task so that the unspecified game became soccer. However, if we additionally requested that the game was a board game, this clearly influenced the generated ideas, implying a change in task interpretation, memory search, and idea production.

Publication VI investigated the dynamics of design IG in two design experiments. In the first experiment, the subjects regularly began generating ideas from the most common categories in overall. This supports the semantic and temporal clustering previously observed in relation to SIAM. As these clusters were exhausted they moved on to generate ideas from less typical categories. This is understandable if the memory search part is functioning stochastically as assumed. The most typical categories will be explored first, because they are the easiest to access. The second experiment was focused on the use of pictorial examples to stimulate design. Both experiments tracked the time dimension and showed that the designers were always more productive and categorically most flexible during the first 15 or 20 min time period. The results about the stimulation showed that in the early phase, the quality of stimulus does not make a difference. However, novel, heterogeneous stimuli can be beneficial if administered during the duration of idea generation. This fits the model if we assume that initial IG is a more bottom-up activity and attention to examples is paid later on.

The study presented in Publication V does not directly associate with any of the parameters of the model. However, it becomes relevant for the discussion once we consider the justification and the need for the theory. The study documents the fact that people taking part in idea generation are not recognizing the IG process, its features and special needs. Particularly group work may turn out to feel frustrating because the students have not learned the right ‘creative’ practices required for productive idea generation. This supports the argument about the implicit nature of idea generation as a process which can be carried out quite effortlessly and without much thought to it.

3.3 Theoretical Applications of the Model

Having now laid out a suggestion about how design IG as a cognitive activity might be organized, let us analyze some idea-generation practices presented in section 1.3.2. As indicated in the following paragraphs, some these observations have already been made in the literature, but some are presented here for the first time. For instance, stimulation from prototyping and time pressure effects are likely analyzed here for the first time. Starting from the IG methods associated with product design, it is argued that these methods can produce two kinds of effects: **memory search** and **task constraints** effects. As I will next present these effects, it should be noted that these categories are not mutually exclusive; the same method can produce both kinds of effects.

Memory search, as described above, is susceptible to many variables. External stimuli, product examples and ideas from other designers, can produce both negative and positive influences. In SIAM, it is assumed that design fixation must take effect via regular memory search mechanisms. This means that fixation can affect the search-cue-formation process, later emerging sampling set, or associations in LTM. The example (stimuli) that initially activates the participants' long-term memory representations also strengthens the association between the search cue (and consecutively the task description) and those particular solutions in memory. This leads to their augmented probability of being sampled later on in the memory-search process, which manifests in design fixation. (Nijstad & Stroebe, 2006)

The impact of examples may not be solely detrimental. The beneficial effects of external ideas have been investigated under the topic of cognitive stimulation. Psychologists and design researchers have repeatedly shown how idea exposure can positively influence one's ability to produce ideas (e.g. Brown et al., 1998; Coskun et al., 2000; Dugosh & Paulus, 2005; Dugosh et al., 2000; Nijstad et al., 2002; Perttula & Sipilä, 2007). The primary mechanism of cognitive stimulation is that the presented ideas can be used in the search cue providing access to knowledge that would have been inaccessible without the stimuli. This facilitates switching between idea categories (Nijstad and Stroebe, 2006) which is considered to be an indicator of flexibility in IG. This will also speed up knowledge retrieval in contrast to working without examples, because the time required to assemble and change the cue is reduced. The model also predicts that the initial overlap of stereotypical ideas might be evaded by administering uncommon examples (Nijstad et al., 2002). It has been already shown that if examples are from similar or the same categories, then they will lead to a search cue which effectively probes the same mental categories (Brown et al., 1998; Nijstad et al., 2002) and fewer ideas will be found from other categories. The timing of example ideas is also essential as providing a host of ideas at once will give each example less attention than they would receive if they were presented during the IG process, as usually happens in group settings (Coskun et al., 2000; Perttula & Sipilä, 2007).

In design world, some design techniques might be linked to cognitive stimulation effects. What cognitive function do prototypes and sketches serve? It have been previously claimed that sketching can off-load working memory load (Bilda & Gero, 2007; Bilda, Gero, & Purcell, 2006). As discussed before, prototypes and sketches can act as communication devices in a design team. For an individual designer, especially prototypes seem to serve a discovery and memory function, parts of what Ulrich and Eppinger (2008) discussed under the umbrella of 'learning' function. This function could be argued to be similar to incubation (Ellwood et al., 2009; Mandler, 1994; Shah, Smith et al., 2003; S. M. Smith, 1995; Snyder et al., 2004; Weisberg, 1993) the process of externalizing thinking in prototypes and sketches can shift the attention away from fixated memory. As the person returns to process the task and the prototype, the IG process can continue stimulated by the prototype or the evaluation of the prototype may lead into new problem formulations that can provide a fresh start for the IG process. However, to my best knowledge, these aspects of prototyping as variables in a cognitive process have not been much studied. For example, Dow and associates have recently examined similar questions (Dow, Heddleston, & Klemmer, 2009) but not quite touched this issue. We need first to define testable hypotheses regarding the significance of prototypes and then trial them in design experiments.

Task constraints present another category effects which seem to have their primary influence to the final phase of IG, evaluation (stage 4 in Figure 3.1). It is assumed that the more requirements are added by some method, the more difficult it becomes to generate ideas. Because of multiple constraints that all set requirements for what is an acceptable idea together with designer's personal aspirations (style and level of doing things, see Harfield, 2007). For instance, consider techniques that gather user needs as an inspiration for design. As more needs are expressed, it becomes progressively more difficult to find a solution satisfying them all. Compare this to impossible tasks of designing either one car or one bag for all. This is also similar to the Brainstorming rule (Osborn, 1957) 'no criticism' which basically opposes the presentation of seemingly impossible constraints.

In response to the challenge of multiple constraints, Cross (2008) presents several techniques for grouping and analyzing multiple product requirements, in a way similar to Alexander's analysis of village design requirements (Alexander, 1963). Consequently, it seems justified to avoid using comprehensive user needs and technical constraints sets in the early phases of conceptual design. This also seems to be distinctive between the two introduced disciplines, product and interaction design. In product design the question of 'what to design' seems often to be given beforehand and a certain user need is fixed, like in the process description from Ulrich and Eppinger (2008). In that model, it was visible that in concept development, needs should be defined early on and are distinct from IG. In contrast, interaction design methods begin from exploring 'what the user might need' which gets mingled with 'what to design', certainly contributing to the perceived the complexity of the task. In interaction design it does not seem so clear that user needs and requirements are entirely settled before the first suggestions about the design are made. This also shows in the nature of IG methods introduced in section 1.3.2.

Time constraints were reviewed for Publication IV. However, that paper did not articulate how different time-related effects might be grounded in a cognitive theory of design IG. In section 2.3.3 three categories of time effects were introduced: *incubation*, *productivity over time*, and *time pressure*. The main effect of *productivity over time* was the initial boost in productivity witnessed during the first 4-5 minutes of the session. This is fairly easy to understand in terms of the memory sampling mechanisms. The memory search initially may yield a large result set with many target items. While these are being retrieved for IG, the ratio of new targets and old targets turns into a less favorable one as the memory search continues. In any case, the efficiency decreases. If the search set is not updated by a change of the cues, (for instance, using a frame of reference shifting studied by Shah et al., 2003), it will get progressively more difficult to retrieve new ideas. This will first challenge the idea production as there is a lack of new input, and then slowly affect the whole idea generation process. The same explanation can be applied to *incubation* as well. If we assume that active WM contents are differentiated from the rest of LTM by some activation value, then it follows that this value may 'decay' and make the associated LTM content more difficult to access as more time goes by. This is what happens during incubation period. As the traces between previous solution attempts decay, proactive interference (e.g. in Feldman Barrett et al., 2004) caused by previous solution attempts (retrieved LTM contents) vanishes and new memories can be retrieved. This provides a way out of mental 'ruts' (S. M. Smith, 1995).

Time pressure can affect *recall* and *production* components of the memory-based IG part. Recalling information from memory is not an error free process. The desired information, such as your mother's maiden name, or her birthday in the worst case, may be difficult to retrieve if it has not been recently rehearsed. The retrieval may fail or slow down. In idea generation context, the lack of time may result in constrained memory sampling and recall. Some might label this as reduced exploration of the problem space (Shah, Vargas Hernandez et al., 2003). As a consequence, the ingredients for the generation phase will be more stereotypical and less novel. It could be hypothesized that of all possible combinations of the ingredients, only the most obvious or already existing solutions will be generated and output if the time pressure is high.

4 Discussion

In this chapter I evaluate and recap the main contributions of this thesis. I will show where and how the presented design theory might be useful and what sorts of issues it has. As a conclusion for the work, I discuss requirements and visions for design cognition research in the future.

4.1 Contribution

In this thesis I have advocated a cognitive theory of idea generation which describes the early phases of conceptual design. I have taken the perspective of a theorist. I believe that in building a cognitive theory of conceptual design, it is wiser to start from robust, state-of-the-art psychological constructs. These are the invariants derived from the study of people, properties of human beings that will remain constant for years to come, no matter what sort new methodologies arise or creativity support tools (Shneiderman, 2007) be introduced. As long as the main responsibility in ideation rests on the hands of human designers and is not invested in an artificial or augmented intelligence, information about how people design, the psychology of design, will be the most reliable source for all design related theorizing. Of course, to a pragmatist all of this may sound insignificant, but as a theorist, I see no better options to hang our hopes of developing sustainable view of what design is and how designers manage it.

I believe that that the main findings here regard the nature of design idea generation as a synthetic, productive activity (Publication I) and the claim that productivity is largely based on the capacity to access material found in designers' memory. There is no denying that there is much more to idea generation than just accessing past memories and combining them. However, I do think that these factors are a very prominent aspect underlying the results that have been acquired in the laboratory studies of design IG like those presented as a part of this thesis.

The theory itself presents an increment to a model IG called SIAM (Nijstad & Stroebe, 2006). This means that the main contribution is an adaptation and modification of an existing generic psychological model to describe IG in conceptual design. Although it is admitted that the scope of the present theory does not match some other cognitive formulations of design, the strength of the present work is to describe a selected part of the process with increased precision. This is very difficult to attain if we start from more extensive models trying to cover the whole spectrum of design IG.

4.2 Areas of Application

The design cognition approach advocated in this thesis produces knowledge that is potentially beneficial on two fronts: in the **development of design methods** and in **design education**. These fields are necessarily related to each other. Even though company-specific best practices exist, they do not emerge from a scratch. The methodological skills gained through education will shape this process. This should be particularly important in societies such as in Finland, in which the level of education is generally high. In their preface, Ulrich and Eppinger (2008) describe this relation as follows: "*product development --- is like sailing: proficiency is gained through practice, but some theory of how sails work and some instruction in the mechanics (and even tricks) of operating the boat help tremendously*."

In Publication IV we demonstrated that the awareness of and competence in concept design methods among Finnish future designers was limited. Considering the amount of new design methodological knowledge available, the education promoting explicit training in creative practice is lagging behind. Design disciplines have traditionally promoted 'learning by doing' and 'learning by watching' approaches which effectively transfer existing tacit knowledge (Nonaka & Takeuchi, 1995). I believe that this learning process could be facilitated by guiding future designers also in theory about how creative processes unfold effectively and purposefully. I do not believe that there will ever be a ready-made selection of methods that can tackle each and every creative challenge in product design. However, I do think that the design education could do better in equipping students to embrace future tasks. Stolterman (1994) notes that it is important for education to eradicate the ideals of 'romantic' (inspirational) design thinking and teach students to understand the nature of their work. In the present context, this would mean that the emphasis shifts from 'creative genius' to a trained idea-ready practitioner.

Development of design methodology is a controversial topic. On one hand, the hope of achieving an ultimate, rational methodology has gone out long ago, but on the other hand, there is no denying that both product and interaction design currently boost a wide repertoire of design aids. It was previously stated that early attempts to codify the design process with design methods went eventually out of fashion (Cross, 1984). Then again, the methods did not die out and this is probably because designers have maintained an urge to clear out the fuzzy front-end with what ever new broom stick, or IG method, becomes available. The problem is that if serious design scholars refuse to commit to method development and evaluation, who is going to guarantee that the methods promoted by various independent consultancies really provide any advantage for the design organization? I think this is where some sort of revival design methodology with healthy precautions is required to meet this challenge.

One could claim that the kind of cognitive design theory and empirical IG studies do not really provide answers to the methods riddle, because practice is too far from research. But I argue that any creativity method that is in opposition to the proposed basic psychological mechanisms will have a weak stance and should require strong experimental evidence to support their adoption. If this evidence can be provided this would necessarily point out the need to rethink the psychological theory as well. Given the robust research tradition in experimental psychology, I do not expect this to happen. This could be compared to the domain of medicine, where the idea of evidence-based practice is fundamental to the adoption of any new treatment.

Finally, some *implications for design IG practice* can be made based on the present theory. Consider the productivity in a typical free-form IG session (see Figure 2.2 on p. 48). It seems obvious that this can be altered by providing additional cues for the IG process on appropriate intervals, such as every 5-10 minutes. Incubation can also refresh memory search and the use of prior 'kick-start' IG sessions might also be desirable according to the cognitive entrainment theory. In contrast to the findings presented in Publication V, all justified methods that can help to structure the IG phase should be sought as designer education currently in Finland is preparing the future professionals very well for this task.

4.3 Limitations

The development of a cognitive theory by integrating concepts and findings from several fields of study has many challenges. The research area, design IG, was defined based on the prescriptive literature. As discussed in Publication I, prescriptive literature may not be very good starting point if the interest is in developing a design theory to accurately *describe* and understand the cognitive mechanisms required for and involved in real-world early product design. Also, it may not be justified to study IG as a cut out and detached piece of the puzzle, when in reality, IG is not so temporally-constrained activity and is likely intimately coupled with idea evaluation, refinement, and decision making.

Theoretically, maybe the most important assumption in this work concerns *domain independence*. Much of the present theory is based on generalizing results from basic cognitive memory research into an applied area, design research. Also, within design research, I have treated different branches of design equivalent. By assuming domain independence, I have been able to establish a theoretical framework of how idea generation in design might happen, relying on these different areas of study. One might question is this assumption warranted or not. This issue is fundamental in psychology as well. Starting from the organization principles of cognition (Fodor, 1983; Pylyshyn, 1984) and extending to the theories of creativity (Brattico & Liikkanen, 2009), one can ask whether cognitive mechanisms and capacities underlying creative behavior are shared. The proponents of the modular approach to cognition and those believing in a strong influence of acquired expertise, might refute some of the evidence that I have used to support my arguments. For instance, does the different structure of work in architectural design impose such requirements for thinking processes that the basics of cognitive system evolve into a qualitatively different form (in terms of process and knowledge) as a consequence of adapting to a different task environment? What's more, do fundamental cognitive capacities, memory search for instance, differ from knowledge domain to knowledge domain?

From neuropsychology, we know that the memory for some categories of knowledge is modularized and can be dissociated, e.g. memory for tools (names, functions) can be lost specifically as a result of a brain damage (e.g. in Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003; Puce, Allison, Gore, & McCarthy, 1995). Should we expect that this kind of organization to affect behaviors, such as IG, that rely on memory access? I see no reason to believe that there should be inherent, qualitative differences between domains, just acquired differences even if the different knowledge domains are physically localized to different cortical areas. And on the other extreme, we have theorists who propose that the human capacity for creativity is mainly derived from one cognitive structure that has provided the whole human race its competitive edge in the evolution. For instance, Corballis (1991) has argued that a single gene mutation has brought forth the human capacity for creativity, which is expressed in a psychological construct called Generative Assembling Device. This suggests that creative thinking might be domain independent and theories and evidence on domain might have relevance for other areas as well.

Among design theorists, Visser (2009) has just recently proposed a cognitively-oriented generic-design hypothesis. Considering evidence from different design and non-design studies, he concludes that "*the commonalities between all different forms of design thinking are sufficiently distinctive from the characteristics of other cognitive activities, to consider design a specific, generic cognitive activity*." (*ibid.,* p. 216) From a very different perspective, Krippendorff's semantic view of design (Krippendorff, 2006) makes design seem highly domain dependent. Following his argument, if different design domains present autonomous language games, does not the reality, including all forms of design, also become social constructs? This would render all domains with distinct vocabulary incompatible. The discourse debate has a strong philosophical drift, I will avoid entering it too much. I only present one counter argument. The view I hold relies on Kantian psychological ontology. We perceive and act on the world in a particular way because we are humans. Our mind is a special construct that does have some flexibility to realize rules of multiple language games, but it also has machinery with a fixed set of 'nuts and bolts' that make these games work. All thinking is not linguistic and in particular design of visual entities may be one activity in which the non-linguistic, non-conceptual, but meaningful and functional thinking flourishes. Thus I think that the semantic turn does not destroy the possibility for a domain general, psychological science of design.

The scope of the presented theory is also quite limited and abstract with regards to the various practices prevalent in modern product design. The empirical data I have brought to bear are derived from isolated design students working on pen and paper. One might argue that design thinking in situations that apply CAD and other 'creativity support tools' may involve and evoke cognitive capacities (and surely different design discourses) that are not included in the model. However, to my best knowledge there is no particular reason to believe that this would be the case, but this is clearly an empirical question worth examining.

The empirical studies of design IG are also susceptible to other kinds of criticism. The challenges mentioned by Vargas Hernandez, Shah, and Smith (2007) include the inability to distinguish between relevant and irrelevant IG components and their interactions, the number of studies required to assess all active IG components, the inability to generalize experimental outcomes to different design tasks and contexts, and the poor understanding of the causal chain in ideation. It can be argued that the studies conducted by the same authors already provides evidence that experimental design research can defend itself against many points of criticism (Shah et al., 2000; Shah, Smith et al., 2003; Vargas Hernandez et al., 2007). The experimental setups applied in design studies can disclose causal relations, even though the difficult issue of pointing out the effective cognitive mechanisms remains.

Problem solving in design cognition.

The present dissertation is strongly tied to the design cognition paradigm and problem solving discourse. For several decades now, design has been generally conceptualized as problem solving (Simon, 1969). The problem solving approach has been a lively for quite long. However, there are concerns whether it can provide adequate answers and descriptions for all aspects of design. One essential difficulty is the separation of problem formulation and solution generation, which has led some to even propose separate problem and solution spaces (Cross, 2007; Dorst & Cross, 2001; see also Harfield, 2007). Even if this would please the design investigator, it will remain hard to digest for a designer. This was stated in Publication I and has been described by others. Jones (1963, p. 10) writes "*The difficulty is that the imagination does not work well unless it is free to alternate between all aspects of the problem, in any order, and at any time, where as logical analysis breaks down if there is the least departure from a systematic step-by-step sequence. It follows that any design method must permit both kinds of thought to proceed together if any progress is to be made. Existing methods depend largely on keeping logic and imagination, problem and solution, apart only by an effort of will, and their failures can largely be ascribed to the difficulty of* ***keeping both these processes going separately in the mind of one person***." (emphasis added) The solution suggested by Jones is to externalize the components as they emerge and thus try to overcome the evident problem of juggling an increasing amount of design requirements and solutions in their memory. However, it does not sound psychologically feasible. It is questionable are there any real, non-trivial design ‘problems’ that can be discovered through a rational analysis only.

Jones is not the only one who has acknowledged difficulties in the problem-solving approach. Thomas and Carroll (1979) discussed a new branch of science called design psychology. They noted that there are problems with the problem solving concepts they had chosen, however, they did not consider any alternatives. During the following years, both cognitive science philosophers (Dreyfus, 1992) and design researchers (Krippendorff, 2006; Schön, 1995) have come to question these kinds of accounts, each for different reasons. However, as a person interested in making progress to the science of design and unraveling the mental mechanisms of creative achievement in this area, I am concerned that that this criticism, however firm it may be, has not been very constructive. If we abandon the problem solving view which has produced a variety of interesting observations and elaborate theory, where do we turn to in order to achieve a psychological science of design? I belief we do not have to wipe out the problem-solving view completely even if we would be prepared for a new paradigm of cognitive theory.

The talks about paradigm shift in design thinking have already been introduced in this volume. For instance, Ylirisku et al. (2009) discusses ‘third paradigm’ or ‘situated’ accounts of design. However, alike Krippendorff and Schön, the discourses and vocabularies adapted by recent paradigm shift proposals are not foremost psychological. They rather talk about design as meaning construction, reflection, focusing and such. But can these concepts be translated to a psychological discourse, or to any other more theoretically powerful discourse? Can multiple discourses not co-exist if they describe different levels of activity?

Interestingly, this issue has been acknowledged in cognitive science pondering similar problems in psychological science. Regarding different levels of theory, Anderson (1990) discusses an issue called the lack of identifiability, which is “*one-to-many mapping from [algorithmic] mechanisms to behavioral functions, and, consequently, identifying the behavioral level will not identify the mechanism.*” (*ibid*., p. 24) This partially describes also the difficulty in combining the rational and situated accounts of design. Although they both talk about the same phenomena, they do not seem to describe the activity at the same level or address the same kind of activities. Rather, they seem to be interested in different properties of design, in which rational approach associates with the investigation of ‘mechanical’ thought and mental process where as situated approach deals hermeneutically with the aspects of design work that can unravel themselves to a human observer. I think that the proper discourse for design theory may be found from a combination of these two. Descriptive terms from situated account, such as reflection in action (Schön, 1995) or focusing (Ylirisku & Buur, 2007) do not replace the need to explicate with what psychologically happens during and after the application of inspirational methods, and similarly, cognitive models of design ideation do not seem capture progressive development of meanings which seems to commonly occur in design.

4.4 Future Work

This work has sparked several ideas for new research and brought up areas of study largely uncharted. To develop the present approach further, I propose four key challenges for design cognition of conceptual design. The first two have been already discussed and the last two will be introduced in the following paragraphs.

- Bridging rational and situated accounts of design for a comprehensive science of design
- Rethinking problem-solution discourse
- Developing computational model of design idea generation
- Testing and formulating a theory of design knowledge

Starting from theoretical developments, the research on IG models is badly short of formal approaches. Computational implementation of the IG model should be among the first steps in elaborating any of the present theories. This would be most conveniently achieved by adopting an existing cognitive framework, such as SOAR (Newell, 1990) or ACT-R (Anderson & Lebiere, 1998) software architecture instead of trying to develop a full-blown cognitive architecture (cf. Vargas Hernandez et al., 2007) from a scratch. Computational model provides an effective way to test the feasibility of the proposal. The model should be able to reproduce IG phenomena, including semantic and temporal clustering, fixation and stimulation effects. Of course the purpose of the model as a portrait of the theory must be recognized. This is because one quickly arising naturalistic, skeptical question is that what can a computer model possibly tell about creative task such idea generation (cf. Boden, 2004). As of 2009 computers are generally not considered original thinkers. I do not expect that computers will soon be able to substitute human designers as idea generators (see Kurtoglu et al., 2009), but I do believe they could have power in assessing the internal validity of different theoretical approaches to IG. Several steps to this direction have been already taken, for instance Gabora (2002) presents her view about the relation of memory and creative thought in a bit more formal sense. Another reason why this has not been done this far is probably related to the state of design knowledge theory and modeling – the next thing on my wish list.

Developing a theory of design knowledge in process is maybe the most important goal for future design cognition researchers. Although there have been plenty of research into design expertise (see Cross, 2004a) and to the 'designerly' ways of thinking (Lawson, 1979, 1990) the insights into the nature of design knowing are sparse. This is particularly obvious if we compare them to the requirements typically set for creating computational models. Building on the traditional cognitive science and artificial intelligence background, I have previously in this work advocated the process and knowledge dichotomy. However, maybe the present state of art of in design research is telling us something about the validity of this assumption. Perhaps the processes involved in design thinking (or know how) are more important and reflect more accurately the special qualities of design thinking. Maybe the continuous development of mental representations in visual and functional forms (cf. Visser, 2009) through various cognitive mechanisms is the crucial part of design knowledge and thinking.

Besides these listed items, there are few suggestions I would like to make. These concern the metaphor of memory, interpretation of design tasks, surprises as parallels in science and design, and learning creativity.

An important detail to this discussion concerns the concept of **human memory as a store of knowledge**. The psychological paradigm that the present work builds on is constructred on the tradition of controlled laboratory experiments (e.g. Raaijmakers & Shiffrin, 1981). The laboratory studies that have explored how people store in and retrieve information from permanent memory, are all assuming a 'recorder' model of memory. This means that the memories are encoded to represent accurately their original target, a percept or mental image. In experiments, in which people learn lists of names, nouns, or verbs, it is very easy to evaluate when the recorder functions properly, memorizes and outputs the right words. This suits the purposes of experimental psychology quite well as the interested in accurately mapping different cognitive capacities. In IG models (SIAM, VHIM, CNMC, Model-L) ideation is equaled with a sort of free recall which may not do justice for the phenomenon.

However, alternative, constructive memory accounts exist in psychology (for example, Schacter, Norman, & Koutstaal, 1998). They point out that retrieval from memory is not as simple as playing back a record. People repeatedly recall events partially right, such as eye witness accounts in the court of law, or can even construct false memories of events that never occurred, like UFO abductees. While this happens predominantly with episodic (autobiographical) memories, the constructive and recorder models of memory should also be explored in the idea generation and design context. If constructive and generative processes would have a major role in recalling design knowledge, then replacing the recorder model with a constructive view might alter (or inform) the process of IG considerably as the processes of information recall and idea production might become more closely coupled.

The idea of memory-search embedded in the present model was adapted quite directly from Unsworth and Engle (2007). It was already noted that details about the memory search regarding the nature and assembly remain vague. For the psychological theory and its applications in IG research, it would be valuable to understand this process. Future studies should investigated effective free-recall strategies for an IG task, such as Cause-cueing proposed by Potter and Balthazard (2004).

Design task interpretation is a major topic that reflects the whole discourse about how we think about design. The question is how design tasks become understood from the brief and transformed into some mental conceptions of the situation. Traditionally, this has been labeled as constructing the design problem or solution spaces. However, as the concept of problem space and design problem in general was questioned before, it also becomes even more challenging to set out a theory of what goes in this process. Figuring out how exactly existing knowledge possessed by the designers comes in contact with a new task is important for understanding design. Harfield (2007) has recently discussed this in length by considering how design tasks turn into designs. He argues that design problems are better to be thought of as design goals. Importantly, the definition of problem is not in direct relation to brief but contains multiple constraints introduced by the designer in the process of developing the 'problem.'

I think that this challenge connects to the previously discussed conflict of situated and rational approach of design. For design cognition, developing the design theory further requires probably some relaxation of the present theoretical constraints. To be able to consider important and difficult approaches such as designer intuition, a wider perspective than typically accepted by cognitive scientists is probably required. One possible solution might be found from the dual-process theories of human psychology (E. R. Smith & DeCoster, 2000) that describe cognitive functioning as an interplay of consciously controlled and effortful operation vs. almost automatic and swift thinking based on well-established knowledge.

Scientific experiments have some similarities to explorations in design. Hypothetic-deductive science relies on empirical hypothesis testing and it can end up producing results that **surprise** the scientists. In design, at the moment when a mental plan turns into an external object, a design sketch, a prototype, or a draft, this may also evoke a surprise (Ylirisku & Buur, 2007). And the surprise may be so considerable that it leads to an enchantment, which may oppose often necessary criticism. The surprise is the similarity in design and science, the difference is the initial state. In science, the surprise may seem more natural as we may have quite poor hypothesis regarding images from the latest research satellite or brain imaging of cerebral activity during movement, so some kind of surprise is granted, but why do we become surprised by our own ideas? Why is perceiving something external so different than imagining an 'identical' design mentally? Why is it so important to output, perceive, analyze, and revise? Is our predictive imagination limited because of bounded working memory capacity, and thus we need to externalize our ideas? Alternative approach for future studies in design cognition would be to consider these design activities from a situated or distributed cognition approach (Clark, 1999; Hutchins, 1995).

Acquiring or **learning creative thinking** in design and also in other creative disciplines remains very much a mystery. Is it possible and how does it happen? Even though attempts to bust the myth of creative genius and explicate the creative process in psychological means have been successful (Weisberg, 2006), the detailed trajectories of achieving success in design are largely unknown. This means that there would be a great opportunity to perform longitudinal (case or quasi-experimental) studies on individuals and design organizations on how creative practices are learnt, applied and developed. For instance, it could be studied that how much can designers develop their capacity for ideation by adopting new methods to create ideas, or otherwise trying to change their thinking.

4.5 Conclusions

In the opening paragraph of this work I claimed the design theory is in a state bewilderment. Did this thesis manage to reduce this entropy? My purpose has been to illustrate that there is unexploited potential in bringing together state of the art psychological theory and applying it to design research. However, I have also admitted that traditional cognitive science is not equipped to fully handle topics such as conceptual design even if recent developments, such as creative cognition movement, are considered. In my opinion, there are two ways out of this dead end. Either a student interesting in contributing to the science of design must drop prejudice and bravely leave the old and go looking for a discourse and methodology that might best help in achieving a better theory. Or alternatively, one can go looking, but with the eye that what ever comes up could be possibly integrated with what ever working solution is already available at hand. As a cognitive scientist, I prefer the latter option. I see cognitive science not as a collection of facts from 60s and 70s, but as an evolving way of thinking about complex information processing. Its past victories and failures should not blind us from the scientific realism and seeking exact answers to questions, such as, concerning human creativity in design, as a part of a psychological science of design.

How did we end up in the present status quo? If we consider the level of design practices, I think that Krippendorff (2006) is on the right track as he announces a new era of design emerging from the transition from technology-centered to user-centered design. What follows from this tradition is essentially a break down of old design patterns. Design is changing because user-centered constraints have overridden technical constraints. And where as technical constraints could be fixed and development of new solutions temporally frozen, human-centered constraints seem to avoid formalization or stabilization. I agree with Krippendorff that user-related constraints can not (or never) solely determine design, but they have a huge influence. Take for instance participatory design including prototypes. It is very typical that user requirements evolve with the prototypes as users become to grasp what the artifact really is and how it concerns them. Psychologically this means that 'wicked problems' have just become more wicked and the matter of finding out what the problem is ever more complicated. From another perspective one could claim that these constraints are not actually new, designers have always imposed some similar, implicit constraints upon their work (cf. Harfield, 2007) but UCD has just made them explicit and emphasized their importance..

I do not believe that social constructivism, as advocated by Krippendorff (*ibid*.) will become the true discourse of design. It may have an advantage for developing a *science for design,* but as a science *of* design I am inclined to favor the cognitive approach. This said, cognitive approach must break out of the problem solving perspective into a theory of human activity where situated and embodied (Clark, 1999) aspects of designing are prominent, but *not mystified*. This needs to be emphasized. Even if we include radically new parts to the psychological theory of design, it must be laid out in similar way as any existing problem-solving part that is of an ancient origin. It may be so that having a pair of hands and a pen is much more essential for designing than the virtue of stimulated access to long-term memory, but we need to be able to articulate this in plausible terms if it is to be accepted as a core part of the cognitive theory.

I hope that future theoretical descriptions of design will be able to define concepts such as focusing or reflecting in cognitive terms, to find a common ground between the rational and situated accounts. One important aspect that they must explain is the power of externalized thinking, or particular situated activity, prototyping, sketching, and acting out ideas. All these aspects currently define the most advanced and creative design organizations. A proper theory of conceptual design must be able to pinpoint how they work, why they work, and what are their limits. The last notion will be probably the most important for designers who are pragmatically oriented and not just interested in browsing the design research literature to gain understanding how the wonderful system of human cognition keeps the cultural evolution going.

It must be admitted that the view of design IG considered here is rather abstract and simplified. For this reason I have also tried to avoid talking about creativity, when ever possible. I see that from a simple, associative IG view of design cognition, one can develop an elaborate view in which conceptual design is characterized as unified development and integration of multiple constraints and solutions satisfying them. Rather than problem solving, design is a sustained process of solution/problem definition in which new constraints and solutions are continuously discovered and tried to fit into one big puzzle (Harfield, 2007). This is particularly true for the human-centered design projects. The idea of constraint satisfaction can lead us to think about design work and human creativity in general.

I propose that the existence of constraints relates to a generic understanding of the world or a function of sense making. The constraints are adapted as a way of adapting to the regularities and affordances or dispositions of the world. Through learning the way world is, and maybe more importantly how it works (sense about the world or world knowledge), some groups and constellations of constraints become fixed. Overcoming and reconnecting these constraints requires creativity but also an attitude or a cognitive strategy of giving up the fixed world knowledge. This theoretical argument might best describe the difference in the creativity between children under 10 years old and adults. This difference has also been captured by psychometric instruments, such as Torrance Tests of Creative Thinking (Torrance, 1974), showing that generally after ten years of age the traditional divergent thinking (as defined by Torrance, *ibid*.) gives away for restrained, norm-embracing thinking which develops more and more elaborate. Elaboration here means responding to a greater number of constraints or requirements. I see that this ever evolving embellishment is related to the accumulating amount of world knowledge in which the connections of even remote information become interconnected in a way that *is coherent with the existing world*. However, although the understanding of the world increases, the capacity for unconventional, divergent thinking decreases. The demands of creative thinking are thus in conflict with the typical way of human knowledge acquisition. And this world knowledge is just what separates humans from artificial intelligences according to Dreyfuss (1992).

This view of creativity implicates that the bonds of normal thinking and sense making of the world must be broken down in order to enter the creative thinking domain. There are clearly differences between individuals in the typical capacity to perform this type of thinking. For some reason, some individuals are less bounded to the traditional world knowledge and are constantly more capable of bending the laws of the world and acting creatively. This also suggests that people perceived creative will more often be at odds with the conventions of the world. The relation of creativity and humor may be debated (O'Quin & Derks, 1997), but nevertheless the good humors seem to be distributed in western cultures in a similar way to high divergent thinking capacity. This implies that creativity might be bound to cognitive domains (be domain dependent) as people may not exhibit similar creativity over all areas, and may actually want restrain certain areas of life, certain discourses from being inventive. Consider for instance religious fundamentalists who despite utmost convergence and logical thinking on one side may be highly successful in exploring new violent methods to disseminate their message.

Returning to more peaceful designs topics, different kinds of design creativity that may suit the different phases of professional design practice. Convergent thinking and convergent creativity may be required in situations where multiple existing constraints need to be adhered to. In product development, this kind of a situation might be the design of a next generation paper-machine with an open-belt extended nip press (Saariluoma et al., 2006). But for early phases of conceptual design, I believe that the extensive exploration of all design opportunities, 'divergent thinking' will be more important. Hence the methods and practices that help designers to advance on this are desired. And therefore, to develop them, we also need a psychological science of design.

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