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IDEA GENERATION IN ENGINEERING DESIGN: APPLICATION OF A MEMORY SEARCH PERSPECTIVE AND SOME EXPERIMENTAL STUDIES

Doctoral Dissertation

Matti Kalevi Perttula

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Department of Mechanical Engineering
Machine Design

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Department of Mechanical Engineering
Machine Design

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Author Matti Kalevi Perttula

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Idea Generation in Engineering Design: Application of a Memory Search Perspective and Some Experimental Studies

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Field of research	Engineering Design and Cognitive Psychology
Opponent(s)	Professor Gabriela Goldschmidt, Professor Jan-Gunnar Persson
Supervisor	Professor Kalevi Ekman
(Instructor)	Professor Kalevi Ekman

Abstract. Emphasis on creativity and innovation differentiates product design from many other organizational tasks. Designers need to be creative on demand, since design projects involve several occasions where a design team faces the challenge of finding a novel solution for an identified design problem. Thus, the ability to solve design problems productively by means of divergent idea generation is a precondition for finding appropriate solutions. At the same time, procedures and methods for idea generation are often based on intuitive belief systems rather than empirically validated theory. The general aim of this thesis was to address this knowledge gap between theory and practice.

A prerequisite for designing better procedures for idea generation is to achieve a basic understanding on how ideas actually come into being through conceiving the characteristics of the cognitive processes and structures that underlie this endeavor. The general approach taken here was to apply concepts and theories from psychology to the study of idea generation in the specialized discipline of engineering design. The research framework includes discussing psychological concepts, such as, creativity, memory search, and knowledge representation, along with describing an objective technique for assessing performance in terms of the number and variety of ideas produced during a session.

A specific objective of the study was to demonstrate and explain how and why externally-imposed examples may affect performance in design idea generation. Example exposure is conceptually similar to idea exchange that takes place in group idea generation meetings, therefore this issue was found relevant for research and practice. Recent theory and empirical evidence propose that idea exposure may both stimulate and interfere with generative processes underlying idea generation. A series of experimental studies was performed to study the extent to which these effects influenced performance in design idea generation. Contrary to prior studies, examples were shown to have very little effect on total performance, after considering some structural and temporal patterns that emerge in design idea generation.

This study shows that idea generation is not a random process governed solely by an individual's personal trait, but a relatively structured process that can be explained in terms of memory cognition. A new model of the idea generation process is proposed here, formed from the perspective of internal memory search. The model conceptualizes idea generation as a repeated search process which includes three main phases: problem interpretation, memory search, and knowledge adaptation, as well as two decision gates.

Keywords idea generation, memory search, design cognition, example exposure

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Väitöskirjan nimi Ideointi tuotesuunnittelussa: Muistinäkökulman soveltaminen ja joitain kokeellisia tutkimuksia	
Käsikirjoituksen jättämispäivämäärä 26.5.2006	Väitöstilaisuuden ajankohta 24.11.2006
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Osasto Konetekniikka Laboratorio Koneensuunnittelu Tutkimusala Suunnittelu ja Kognitiivinen Psykologia Vastaväittäjä(t) Professori Gabriela Goldschmidt, Professori Steven M. Smith Työn valvoja Professori Kalevi Ekman (Työn ohjaaja) Professori Kalevi Ekman	

Tiivistelmä. Luovuuden ja innovaation painottaminen erottaa tuotesuunnittelun useista muista organisatorisista tehtävistä. Suunnittelijoiden täytyy olla luovia vaadittaessa, sillä suunnitteluryhmän on projektin aikana löydettävä uudenlainen ratkaisu tunnistettuun suunnitteluongelmaan useita kertoja. Tämän vuoksi kyky tuottaa paljon ratkaisuja suunnitteluongelmiin laajakatseisen ideoinnin avulla on soveltuvien ratkaisujen löytämisen edellytys. Ideointimenetelmät ja -menettelytavat perustuvat yleensä kuitenkin intuitiivisiin uskomuksiin empiirisesti validoidun teorian sijaan. Tässä tutkimuksessa tutkitaan tätä teorian ja käytännön välistä kuilua.

Pystyäksemme kehittämään parempia ideointimenetelmiä vaaditaan perusymmärrystä siitä, miten ideat oikeasti syntyvät. Tämä edellyttää ymmärrystä niistä kognitiivisista prosesseista ja rakenteista, joihin ideointi perustuu. Työssä käytetty yleinen lähestymistapa oli soveltaa psykologisia konsepteja ja teorioita tuotesuunnitteluun liittyvän ideoinnin tutkimiseen. Tutkimuksessa pohditaan psykologisia konsepteja, kuten, luovuus, muistihaku ja tiedon esitykset, sekä kuvataan objektiivinen tekniikka ideoinnin tehokkuuden mittaamiseen, jonka perustana on session aikana tuotettujen ideoiden määrän ja poikkeavuuden mittaaminen.

Tutkimuksen erityisenä tavoitteena oli osoittaa ja selittää, kuinka esimerkeille altistaminen vaikuttaa ideoinnin onnistumiseen. Esimerkeille altistamisella on yhtäläisyyksiä ryhmässä tapahtuvaan ideoidenvaihtoon, minkä vuoksi tämä asia koettiin tärkeäksi teorian ja käytännön kannalta. Viimeaikainen teoria esittää, että esimerkit voivat samanaikaisesti stimuloida ja häiritä tuottavia prosesseja, joihin ideointi pohjautuu. Koesarjan avulla tutkittiin näiden tekijöiden vaikutusta suunnitteluideointiin. Vastoin aiempien tutkimusten tuloksia, sen jälkeen kun tietyt rakenteelliset ja aikaan liittyvät vaikutukset huomioitiin, esimerkeillä näytettiin olevan hyvin vähän vaikutusta kokonaissuoritukseen.

Tämä tutkimus osoittaa, että ideointi ei ole summittaista ja ainoastaan yksilön luonteenpiirteisiin liittyvää, vaan se on suhteellisen jäsennelty prosessi, joka voidaan selittää muistikognition avulla. Työssä esitetään ideointiprosessista uusi malli, joka muodostettiin sisäisen muistihaun näkökulmasta. Malli hahmottaa ideoinnin toistettavaksi etsintäprosessiksi, joka koostuu kolmesta päävaiheesta, jotka ovat ongelman tulkinta, muistista etsiminen ja tiedon soveltaminen, sekä kahdesta päätöksentekoportista.

Asiasanat ideointi, muistihaku, suunnittelukognitio, esimerkeille altistaminen	
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PREFACE

The work presented in this dissertation was conducted during the years 2004 to 2006 at the Department of Mechanical Engineering at Helsinki University of Technology (TKK) and at the Center for Design Research at Stanford University. This dissertation includes a partial report of findings from research project Navigo (2004-2006) funded by the Academy of Finland. The Navigo project team included Professor Kalevi Ekman, MA Lassi Liikkanen, MA Pekka Sipilä, and M.Sc. Aleksi Kuitunen.

I express my gratitude to Professor Kalevi Ekman for his guidance throughout my under- and postgraduate studies at TKK, and to Dr. Ade Mabogunje and Lassi Liikkanen for our insightful discussions while writing the dissertation. I also thank Professors Gabriela Goldschmidt (Technion) and Steve M. Smith (Texas A&M) for reviewing the dissertation. In addition, I am grateful for the Academy of Finland, Finnish Funding Agency for Technology and Innovation (Tekes), and Yrjö and Senja Koivusen Säätiö for funding this research.

I would further like to thank my colleagues, who I have been privileged to meet and work with during my research. My sincere gratitude goes also to all my friends. Finally, I thank Laura and my family: father Pekka, mother Pirkko, and brother Antti, for their loving care and support.

Matti Perttula — Espoo, 16th of October, 2006

LIST OF PUBLICATIONS

This thesis contains an overview of the following six publications:

I. Perttula, M., Krause, C., and Sipilä, P., 2006, "Does idea exchange promote productivity in design idea generation?", International Journal of CoCreation in Design and the Arts, Volume 2, Number 3, pages 125-138. © Taylor & Francis 2006.

II. Perttula, M., and Sipilä, P., 2006, "The idea exposure paradigm in design idea generation", Journal of Engineering Design, in press. © Taylor & Francis 2006.

III. Perttula, M., and Liikkanen, L., 2006, "Structural tendencies and exposure effects in design idea generation", In: Proceedings of ASME International Design Engineering Technical Conferences, CD-ROM. © ASME 2006.

IV. Perttula, M., and Liikkanen, L., 2006, ”Exposure effects in design idea generation: Unconscious plagiarism or a product of sampling probability?", In: Jonsson, M. and Unnporsson, R. (Eds.), Proceedings of NordDesign 2006, Reykjavik: University of Iceland, pages 42-55. © University of Iceland and the authors 2006.

V. Perttula, M., and Liikkanen, L., 2005, "Cue-based memory probing in idea generation", In: Gero, J.S. and Maher, M.L. (Eds.), Proceedings of Computational and Cognitive Models of Creative Design VI, Australia: University of Sydney, pages 195-210. © University of Sydney 2005.

VI. Liikkanen, L., and Perttula, M., 2006, "Contextual cueing and verbal stimuli in design idea generation", In: Gero, J.S. (Eds.), Proceedings of Design Computing and Cognition '06, Springer, pages 619-632. © University of Sydney 2006.

AUTHOR’S CONTRIBUTION

Publication I: The author was responsible for designing, conducting, and analyzing the experiment and writing the article. Pekka Sipilä participated in all phases of the experimentation. Christina Krause helped with analyzing the results of the experiment and commented on early versions of the manuscript.

Publication II: Pekka Sipilä participated in conducting the experiment. The author was responsible for the other phases of the experimentation and writing the article.

Publication III: Lassi Liikkanen participated in analyzing the results of the experiments, and commented on early versions of the manuscript. The author was responsible for the other phases of the experimentation and writing the article. Designing the experiment was a collaborative effort between the two authors.

Publication IV: Lassi Liikkanen conducted the experiment and commented on early versions of the manuscript. The author was responsible for analyzing the results of the experiment and writing the article.

Publication V: The design of the memory search model that forms the basis of the paper, and writing the article was a collaborative effort between Lassi Liikkanen and the author.

Publication VI: Writing the article as well as designing, conducting, and analyzing the experiment was a collaborative effort between Lassi Liikkanen and the author.

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1 INTRODUCTION

1.1 BACKGROUND

Design organizations compete on the basis of innovation. A competitive advantage can be achieved through the design and manufacture of products that are distinct from competing offers. One way to accomplish differentiation is to develop products that have original features in meaningful dimensions. To the extent that these features are protectable as intellectual property, a company can enhance its competitive edge. Innovation is born from creativity, which, in turn, resides in the human resources available to the organization. Creativity is not limited to the new product concepts themselves. Instead, design projects involve several occasions, where the design team faces the challenge of finding a novel solution for some particular sub-system of the general product architecture. A common context for idea generation is an intentional session or meeting, in which a group of persons come together to generate ideas for an identified design problem.

Theory treats idea generation in design as a special type of problem solving activity, which is founded on ill defined problems (e.g. Goel and Pirolli 1992, Goldschmidt 1997). The notion behind calling design tasks “problems” refers to the fact that solutions are not trivial, nor immediately available. Ill defined, in turn, implies that for most design problems, the goal state is not clear i.e. the designer does not have the complete set of solution specifications available. This means that there is more than one solution that delivers the required functionality. Problem spaces for design problems therefore maintain an uncertain and explorative character. It is up to the design team to define and explore the solution space, and eventually find an acceptable solution.

Humans are imperfect as search engines (Busby and Lloyd 1999); individuals and teams tend to focus on a narrow part of the solution space; some valuable solutions are therefore overlooked. However, humans are not generally incompetent to produce diverse and novel output above a given base-line level. If we assume that creativity is something that is not given as a static quality, we also accept the notion that creativity can be learned to become better at solving design problems productively. In this view, verbal instructions or structured creative techniques can be employed to support the creative process.

A number of techniques have been designed to aid in the generation of ideas (see e.g. Osborn 1957, De Bono 1970, Van Gundy 1981). The difficulty with idea generation methodology in general is that there is very little theoretical and empirical evidence that clearly points out direct benefits from their use (Smith 1998, Sternberg and Luvart 1999, Shah et al. 2000). Even more, creative techniques have emerged from more or less arbitrary sources and as a result, the methodological battery lacks a reference to scientific research. Thus, up to this date, much that we know about idea generation is based on intuitive belief systems rather than empirically validated theory. A prerequisite for designing better procedures for idea generation is to achieve a fundamental understanding on how ideas actually come into being through conceiving the characteristics of the cognitive processes and structures that underlie this endeavour. From this stance, the general aim of this thesis is to address the knowledge gap between theory and practice.

1.2 SCOPE AND OBJECTIVES

This work is initiated by the assertion that creative thought can be understood and explained by the same cognitive processes and structures that are involved in non-creative thinking. The approach is to apply psychological concepts and theories to the study of idea generation in the specialized discipline of engineering design. The research framework includes discussing psychological concepts, such as, creative thinking, memory search, and knowledge representation, along with describing an objective technique for assessing performance in idea generation. The empirical part of this thesis includes a series of comparable experiments that were designed to evaluate how exposure to examples affects productivity in design idea generation. Example exposure is conceptually similar to idea exchange that takes place in group idea generation meetings, therefore this issue was found relevant for research and practice.

The general objectives of the thesis are:

- To assemble a research framework for experimentally studying the process and performance aspects of idea generation in engineering design.

- To explore and assess whether specific structural and temporal patterns emerge in a situation where an individual is asked to generate ideas for a given design problem.
- To demonstrate and explain how and why externally-imposed examples may affect performance in design idea generation.
- To conceptualize a model of the design idea generation process based on related psychological theories and concepts.

These questions are studied and addressed in the context of short-term idea generation sessions, in which subjects, educated in the domain of design, attempt to generate as many different ideas as possible for an identified design problem in a fixed amount of time.

1.3 EMPIRICAL APPROACH

The empirical studies presented in this thesis are a partial report from research project Navigo (2004-2006, Academy of Finland). During the project, a total of nine independent idea generation experiments were performed using comparable procedures, of which six are reported in this dissertation. In the experiments university-level design students were asked to generate and visualize ideas for a given design task while some aspects of the session were monitored or conditioned. Experiments were mostly held in a large class-room where all subjects were tested simultaneously. The total number of subjects participating in the studies was about 400; producing an idea pool of some 3500 sketches.

1.4 OUTLINE OF THESIS

In chapter 2, the basic arrangement and theories underlying idea generation are presented. This chapter also includes a description of an objective approach for assessing performance in idea generation. The purpose of Chapter 2 is to define a general framework for studying design idea generation experimentally through drawing tasks. Chapter 3 includes reviewing related theories and earlier empirical studies on relevant areas. The six publications that form the basis of this thesis are summarized in chapter 4. In chapter 5, the results of the study are reviewed and projected on prior theory and research, and implications for practice are discussed along with proposing agendas for future studies.

2 FRAMEWORK

2.1 CREATIVE DESIGN

The purpose of the act of designing is to provide descriptions of physical structures that perform specified functions. In a context where a designer is not allowed access to external information sources, he must be able to utilize his previously acquired knowledge to generate solutions for an identified design problem. The basic arrangement of internal memory-based idea generation is that individuals possess prior knowledge, which they attempt to exploit to solve a given design problem. In this view, proficiency in idea generation is determined by one's ability to activate a wide array of knowledge and adapt this information to meet the requirements of the current situation. From this perspective, the process of idea generation is affected, not only by the factual amount of design knowledge that one has gathered, but also by the way that knowledge is organized, accessed, and exploited.

A creative idea should encompass two characteristics – novelty and usefulness (e.g. Amabile 1983, Sternberg and Luvart 1999). Novelty distinguishes between recalling an entity that previously existed in the presented form, from generating an entity that appears to the individual for the first time, at least in the current context. Usefulness makes a distinction between ideas that are inadequate in the current situation from those that are useful. In engineering design, usefulness is accomplished when an idea is not in conflict with the initial requirements.

What do these fundamentals say about the idea generation process? Even more, why should idea generation in design be studied separately from other disciplines, or for that matter, by using designers as subjects? First, the notion that ideas are based on previous knowledge, means that knowledge must be purposefully and efficiently accessed when one wishes to generate ideas for a given design problem. Therefore, idea generation is best understood as a repeated goal-oriented memory search process. Whereas, the nature of design problems requires that subjects possess domain specific knowledge, meaning that, for instance, a gardener does not have necessary knowledge on how to design, say, hydraulic systems. On the other hand, design, at least in the conceptual stages, can be performed with relatively little knowledge on hard engineering issues, such as, fluid mechanics and tribology. After all, we all are surrounded by designed artefacts whenever we perform our everyday tasks, whether it would be brushing your teeth with a tooth-brush or flying to San Francisco on an Airbus 380. However, it is reasonable to expect that engineers do possess also domain-specific conceptual knowledge that differentiates them from subjects that are naive to design.

How do individuals then come about to generate such novel and useful ideas? After all, the notion that even novel ideas must be based on previous knowledge seems paradoxical. A general premise introduced to resolve this discrepancy is that novel ideas come into being by the combination or re-configuration of prior knowledge (e.g. Mednick 1962). This notion also holds the proposition that creative generation involves other cognitive processes in addition to knowledge retrieval, since people apparently have the ability to synthesize and transform their mental images. Taken these two requirements into consideration, Finke, Ward, and Smith (1992) proposed a research initiative called Creative cognition to the study of creative thinking, which attempts to “identify the specific cognitive processes and structures that contribute to creative acts and products and to develop novel techniques for studying creativity within the context of scientific experiments (Finke et al., 1992, pp. 1).” The basic framework of Creative cognition is a dual-phase model of creative thinking called the Geneplore model (Figure 1). In the generative phase, one forms mental presentations called pre-inventive structures. The pre-inventive structures are then examined and interpreted with various processes in an exploratory phase.

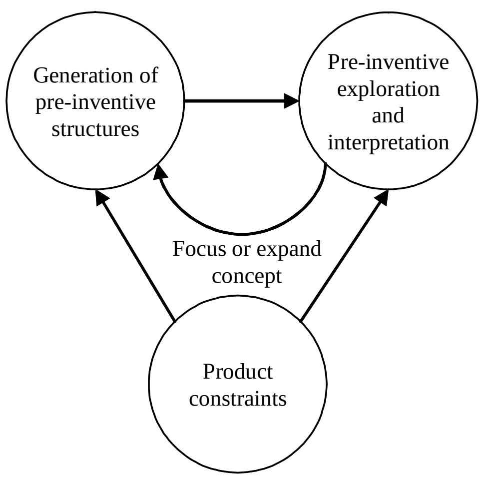


Figure 1. The Geneplore model (adapted from Finke, Ward, and Smith 1992)

In the next section, I will clarify the nature of the different pre-inventive forms that are found relevant in this context. After this, the process of memory search is described in detail. This section is followed by describing the form which ideas take once they are externalized. Then, an objective technique for assessing productivity in idea generation is described.

2.2 KNOWLEDGE REPRESENTATIONS

As described in the framework of creative cognition (Finke et al. 1992), the generative phase of creative thinking results in the formation of a pre-inventive structure, which forms the basis for an externalized idea. Pre-inventive structures are definitive in a sense that they determine the conceptual attributes of the finalized ideas. What are then these pre-inventive structures? According to Finke (1996), pre-inventive structures are visualized patterns and object forms, but they may also include other structures. Relevant forms for design idea generation include also more complete representations than simple object forms, such as models, schemas, cases, and conceptual combinations, which differ by the completeness of the original long-term knowledge representation and by the fact whether they are representations from one or multiple classes.

Next, I will briefly describe some of these different pre-inventive forms. For this purpose, pre-inventive structures are classified by their abstractness (conceptual or specific) into single and multiple class representations. This classification is shown in Table 1. I define an image to be the basic unit or ‘building-block’ for these representations. Finke (1996) uses the term “object form” to be the basic unit (see also “geons” in Biederman 1987), but I prefer to use the term image, since it better captures the fact that knowledge units for engineering designs need to include attributes of both: form and function.

TABLE 1. Classification of some pre-inventive structures based on their generality and categorical organization. Single class pre-inventive structures are stored in memory as single units, whereas multiple class pre-inventive structures represent knowledge that is stored as separate units.

	SINGLE CLASS	MULTIPLE CLASS
Conceptual	Model or schema [a]	Conceptual combination
Specific	Case	Parts assembly

Models are a generalization of a class of designs. Models include a hierarchical representation of conceptual level attributes of a class of artefacts. Example: Sub-systems of the class “automobile” include e.g. wheels, windows, engine, transmission, seats, and steering wheel, and attributes include e.g. quantities (wheels: four) and spatial relations (seats: front and back).

Schemas are more detailed representations of conceptual models; otherwise they are similar, since they present a generalization of a class of artefacts. Schemas in design consist of generalized knowledge from a set of like design cases (Gero 1990). Schemas are therefore knowledge representations that carry detailed knowledge appropriate for a class of designs. Design prototypes are sometimes used as synonyms for schemas. Example: A schema of the class automobile may include detailed representations of the physical properties of the construction, for instance, how the thermal-energy attained from gasoline is converted into rotational force that runs the wheels.

Cases are specific instances of a class of artefacts. Cases are similar to category exemplars; the difference is that category exemplars present a stereotypical case of all objects in a class, whereas the selection of a case is irrespective of its stereotypicity. Example: BMW X5 is a specific case of the class automobiles.

Conceptual combinations (or blends or synthesis) refer to the creation of new knowledge structures through the integration of previously distinct concepts (Mumford et al. 1991). Example: An automobile-like hover-vehicle running on jet engines is a mental synthesis of an automobile and a jet plane.

Parts assembly refers to assembling a new design from separate parts. Hence, there is an important distinction between assembling new concepts from independent specific parts and forming a conceptual combination of distinct concepts. Example: A hybrid power train that uses gasoline and electricity as its energy source. In this case, the two power sources are separate structures, but form a new concept when operated sequentially to deliver a common function.

2.3 MEMORY SEARCH

Memory retrieval is the recovery of stored information, which is required practically for all cognitive tasks. To remember past events, information must be retrieved from memory. Similarly, to generate a design, knowledge or prior solutions need to be retrieved from memory. Long-term memory is the storage in which we record our knowledge. Apparently, we need to be able to recall past events or knowledge when they are needed, and likewise keep them passive or inactive when they are not required for our present task. One of the foundations of memory retrieval is that recall depends on the presence of an effective retrieval cue (Lockhart 2004). A retrieval cue is the element that activates long-term memory representation, which can be either self-generated or provided as external stimulus.

A second established theory in psychology related to memory retrieval and storage is the notion that memory items include contextual attributes. Contextual attributes are encoded to items when they are stored in long-term memory. Knowledge of contextual attributes can be used e.g. to enhance recovery of particular items through contextual cueing (e.g. Godden and Baddeley 1975, Raaijmakers and Shiffrin 1981). Contextual attributes can be sub-divided into independent and interactive context. Interactive context refers to the semantic attributes of the items, whereas independent context refers to the temporal conditions in which the original event was experienced (Baddeley 1982).

A further relevant theory related to memory processes is the notion of an associative memory network (e.g. Collins and Loftus 1975, Raajimakers and Shiffrin 1981, Anderson 1983, Martindale 1995). As stated by Anderson (1983) "…many memory phenomena can be understood in terms of the network structures that encode facts and the network structures which surround these encodings (Anderson 1983 pp. 261)." The basic notion is that semantically related knowledge structures are connected by paths in the memory network, and the strength of a path is a function of the semantic similarity between two concepts. In idea generation, subjects follow these associative paths as they search for task-relevant knowledge i.e. they spread activation in their memory networks.

When discussing idea generation, researchers do not use the term memory retrieval, but memory search. This anecdote captures the dynamic nature and role of the retrieval cue. In one's own mind, a particular retrieval cue evokes a particular source, and therefore the cue must be altered in order to retain a further target (e.g. Nijstad et al. 2002). Of course, knowledge tends to reform and decay in storage, depending on its use, but in a short-term situation, it is more than reasonable to expect that the above said is valid. Searching long-term memory for task-relevant knowledge is not as simple as it may seem. Individuals cannot simply ‘open a catalogue’ and select relevant information after browsing the related data-base. Instead, short-term memory capacity is limited; persons can hold about five to nine information ‘chunks’ active simultaneously (Miller 1956). The search processes must be largely sequential, since idea generation apparently involves sampling much more knowledge than can be kept active at once (e.g. Collins and Loftus 1975, King and Anderson 1976). Thus, idea generation should be understood as a repeated search process, in which the cue has a deterministic influence. Furthermore, replacing or altering the cue is typically more challenging than simply deleting the previous one and forming a new one (which you would have no trouble doing on Google if you were not satisfied with the results of the initial query). Hence, retrieval can be blocked or narrowly focused in the problem space. These incidents are generally related to the concept of fixation in problem solving (see pp. 32-37). Furthermore, as opposite to e.g. internet search engines that mostly use keywords and one-to-one similarity matching, searches in idea generation involve semantic queries. Meaning that, the representation of the cue is richer than its linguistic representation in spoken language. However, linguistic representations, such as nouns, adjectives, and verbs, are helpful in describing the role and nature of the cue.

In addition to altering the cue itself, it may be re-directed by changing the representation of the problem. As will be described, problem representation is analogical to the concept of context in memory, when context is understood as a semantic description of the environment of the to-be-generated design. To describe the coupled nature of the cue and context, a logical starting-point is to consider the elements of the problem description. As an example, consider one of our design tasks, in which we asked subjects to generate ideas for “a device that transfers balls from a playing-field into a goal area.”

The problem description includes one verb (to transfer) and four nouns (device, ball, playing-field, and goal-area). In this case, the subject needs to provide a description of a device (i.e. structure) that transfers balls (i.e. function), whereas the balls, playing-field and the goal-area are features of the environment of the device (i.e. context). Transfer is a high-level function that cannot be changed without changing also the task itself. The terminology used in academic literature says that a subject searches within a mental problem space. A person forms this mental representation of the problem based on a subjective interpretation of the problem description. The subject may either consider that the balls are on a soccer-field or, say, on a dining-table. Intuitively, the transfer function is likely to be enabled by different types of designs in these two contexts. Tilting the field and causing the balls to roll, would be more understandable when the balls are on a table rather than on a soccer-field. Furthermore, the subject may interpret more detailed features of the problem environment, for instance, the material of the balls. Now, if the subject interprets the balls as, say, ping pong balls rather than ones made out of steel, then, he would more likely apply a pneumatic device, such as a blower, to transfer the balls. Hence, transferring a ball from point A to B can be enabled by a number of more detailed actions, such as tilting or blowing, and the probability of generating a particular type of idea is dependent on one's interpretation of the problem description. Taken together, the cognitive mechanisms underlying this behaviour are unchanging, but the subject may change his representation of the problem, which redirects the cue to evoke alternative knowledge sources.

2.4 DESIGN LANGUAGE

Andreasen (1994) calls modelling the "language of the designer". Modelling refers to the visual and verbal expressions of the design artefact. Models take various forms during the design process. Designers tend to start out with simple verbal expressions "a sort-of robot arm", moving on the preliminary sketches that may depict e.g. primary components, spatial arrangements, and initial shape, and eventually, designers move on to more complete models such as three-dimensional computer-generated images.

The models relevant for this work are the preliminary sketches. In the experiments that form the empirical basis of this thesis, subjects were asked to visualize their ideas with simple sketches. The actual instructions, which were kept standard across the experiments, were to use simple sketches that "represent the solution principle and main components of the device". In addition, subjects were requested to include supportive textual annotations when found necessary. Since the sketches themselves were the primary information source and unit of performance analysis, interpreting them in a subjective and consistent manner is a requirement for assessing performance (see next section) and learning about the idea generation process

The act of sketching has received interest in design research (see e.g. Purcell and Gero 1998, Goldschmidt 2003). Sketches play an important role in the early design phases, since they are a common medium for memory support and communication. Even more, sketching gives an idea on the mental imagery processes involved in creative thought. Sketches therefore provide a foundation for a relationship between mental imagery and visual creativity (e.g. Finke 1996). However, sketching requires an advanced ability of visualizing one's explored images, and therefore the final output takes a rough or symbolic without extraordinary visual talent.

Below are some typical examples of how designers verbalize (Ericsson and Simon 1980) their ideas along with the produced sketch. The excerpts are taken from one of the Navigo experiments, details and further analysis can be found in Liikkanen (2005). The original sketches, reproduced in the figures below, included also textual annotations, some of these descriptions were excluded from these particular illustrations for aesthetic reasons. The sketches represent solutions for an automatic watering-device for house-plants.

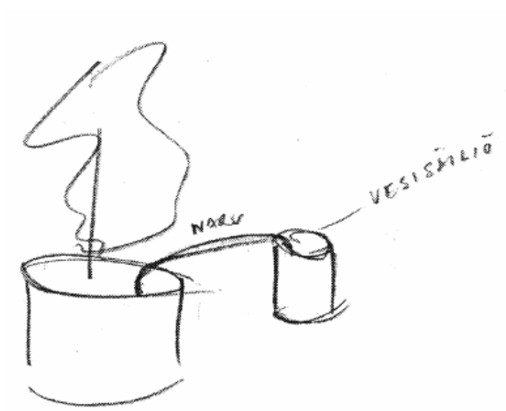


FIGURE 2. Example of student design sketch (#1) produced during idea generation. The concept is based on transferring water to the plant through a string. The solution is based on the capillary-effect, which is a function of the ability of liquid to wet a particular material. (Finnish/English-translation: Naru = String, Vesisäiliö = Water-container)

[00:01:12]: yes, the first thing that came to my mind...was that...there's this...
[00:01:18]: container...from which...
[00:01:21]: goes these some kind of strings there…and then it…
[00:01:27]: goes along those strings...that water...there...to the plant...
[00:01:42]: with the thickness of the string...you can then…
[00:01:45]: determine the amount of water that goes there…

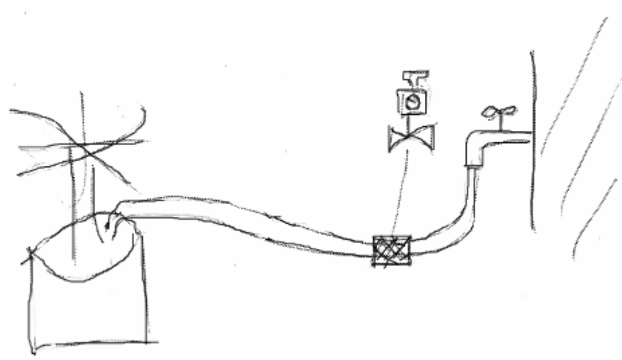


FIGURE 3. Example of student design sketch (#2) produced during idea generation. The idea is to connect a hose to the house-pipe and regulate watering by a timed valve.

[00:15:48]: and then also sort of a concept in which…
[00:15:53]: the water would come directly from the house-pipe…
[00:15:58]: and then you put…
[00:16:04]: a timer there in between…
[00:16:08]: this is the wall...from which comes a faucet..
[00:16:25]: and then you put a pipe there to the flower pot…

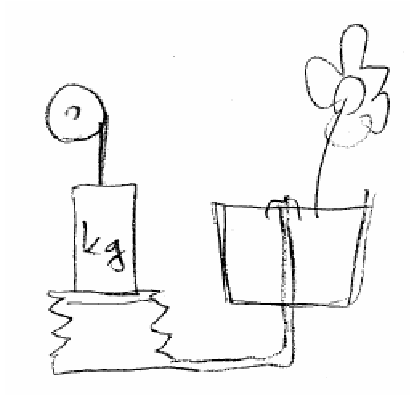


FIGURE 4. Example of student design sketch (#3) produced during idea generation. The idea is based on preliminary adjusting a weight, so that, when it slowly descends, it compresses a water-pump to transfer water to the plant.

[00:43:26]: it's compressed…
[00:43:33]: so we could get the level of water to rise slowly…
[00:43:39]: so we wouldn't need any this type of…
[00:43:44]: expensive technical device to this thing…not electric or other…
[00:44:03]: this type of clock-machinery…that presses…
[00:44:08]: with this type of...clock's weight...so that…
[00:44:17]: presses this type of pump…that compresses it then…
[00:44:25]: it can come from anywhere…say…from here…
[00:44:26]: through the pot...and then...
[00:44:29]: from the water-container…then water comes
[00:44:32]: very slowly...over the edge…so that…
[00:44:35]: there…on the edge...but comes over it…then it just drops…

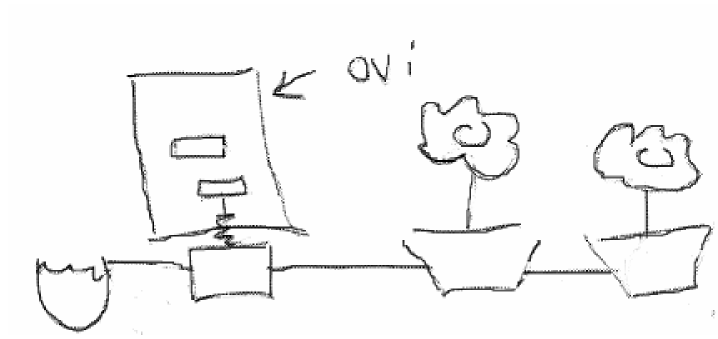


FIGURE 5. Example of student design sketch (#4) produced during idea generation. In this concept, the regulation is based on the daily delivery of a newspaper. Each morning when the newspaper drops from the hatch it presses a water-pump that transfers water to the plant. (F/E: Ovi = Door)

[00:02:50]: flowers need water also in the morning...
[00:02:51]: if there's a mailbox...in the apartment...
[00:02:58]: here's this type of water-pump…
[00:03:05]: and from there...there's a spring…
[00:03:08]: and then here's the suction-side…and there's the bucket…and…
[00:03:15]: the water goes from here to the plant...
[00:03:16]: always when the magazine drops...
[00:03:22]: it presses that system...and...
[00:03:23]: you make a month's order of the magazine...

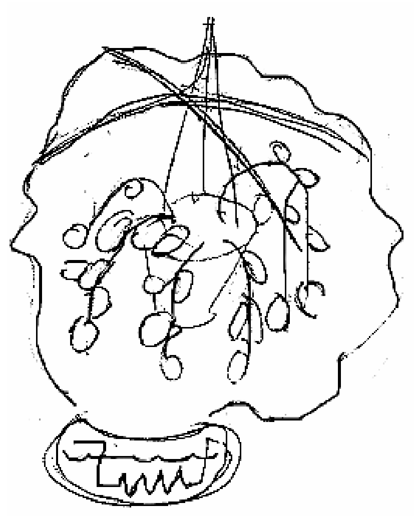


FIGURE 6. Example of student design sketch (#5) produced during idea generation. The idea is to vaporize water with a steamer that ascends to the plant. The plant itself is hanging on a support structure, which also includes a bag to keep the water-steam in proximity of the plant.

[00:17:32]: well...how about...you have those sorts of plants…
[00:17:36]: that takes water sort-of-like...through the air...
[00:17:38]: I've heard that there are also some sorts of plants that do this…
[00:17:41]: if they are grown...they should have that type of…
[00:17:45]: steam-bag...in which you can direct water-steam...
[00:17:50]: a vaporizer there...and…then some kind of…
[00:18:03]: yes, that type of easy-to-use bag that can be placed on...
[00:18:08]: the steaming element...it could be sort of a small...
[00:18:12]: delicately hanging...because...
[00:18:23]: this looks just like the genie-of-the-lamp is coming out...
[00:18:28]: well...anyway...it's like this hanging plant...and...
[00:18:50]: it should be some type of coat-hanger-like...
[00:18:52]: that would keep it...sort-of-like a bag for clothes…
[00:19:00]: let's say...these things are crossed… and you can hang it there...
[00:19:06]: sort of a bag...so the steam won't get away...

There are some typical characteristics in the designers' sketches. The subjects tended to label structures such as "clock-machinery", "vaporizer", "water-pump", "timer", or "valve", instead of describing the structures in more detail, which is typical for early conceptual design. The forms are also often unelaborated in a sense that they represent schematic figures of the main components rather than finished surfaces. Further characteristics can be drawn from the sketches, such as, the spatial layout. Taken together, the sketches are in fact coarse symbolic diagrams of an imagined device, with relatively little detailing on the actual mechanisms of component parts of the system. In the next section, I will present the approach taken to assess idea generation performance from the produced sketches.

2.5 PERFORMANCE ASSESSMENT

Going further into the practicalities associated with a productive task such as design idea generation, a relevant issue is the quantity and quality of task output. Normative design theory favours divergent solution search as a strategy in the early phases of design (Pahl and Beitz 1984). After all, design teams will undoubtedly benefit from generating a number of designs, from which to choose the most promising ones for further refinement and development. Thus, along the propositions of Guilford (1950) and Torrance (1974), effective idea generation should involve generating a large number of ideas from as many categories as possible.

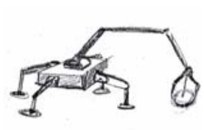
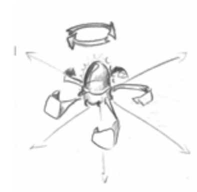
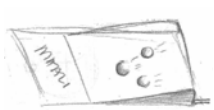
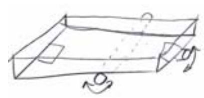
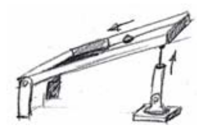
As said earlier, sketches formed the basis for assessing idea generation performance. The experiments include assessments of both - quantitative and qualitative - aspects of the sketches. Qualitative assessment refers to analyzing the content of the sketches, whereas quantitative analysis refers to assessing total productivity. The two primary measures used to assess productivity were: the total number of ideas (or quantity/fluency) and the total number of categories surveyed (or flexibility /diversity/variety).

The number of ideas generated is a common measure of productivity in idea generation research. In the experiments, subjects were given an answering sheet, which had separate frames in which to draw single ideas. This allowed a clear-cut assessment of idea quantity. The subjects were however self-determined on the issue of how to distinguish between two ideas. We did not screen any ideas from the count, even if a subject had depicted only a partial solution in a separate idea-frame. However, a simple count of the ideas tells relatively little about performance. The second measure – number of categories surveyed – gives a more appropriate assessment of subjects' performance. The number of categories surveyed is the original flexibility measure that portrays one's divergent thinking ability. To yield a score for variety, design solutions need to be classified into objectively-defined categories.

The ideas that emerge during idea generation may share resemblance to one-another, or, alternatively, present completely different solutions. Thus, a suggested approach for classifying ideas is to label high-level categories and organize single ideas to those pre-defined categories. For instance, if subjects are required to list ways in which their university can be improved, solutions will fall under relatively well-established categories, such as, classes, campus, building, student life, parking, dorms etc. (Larey and Paulus 1999, Paulus and Brown 2003). Similarly, solutions for design problems are classified according to their general characteristics, but this is done at a functional basis. An approach to accomplish this in an objective manner is to use a problem decomposition scheme, in which the main functionality is sub-divided into primary sub-functions (see e.g. Pahl and Beitz 1984, McAdams et al. 1999, Shah et al. 2003). Despite the fact that sub-systems can be permutated over and over again into further sub-systems, design solutions usually have a limited number of relevant sub-functions at the conceptual abstraction level.

To assess the solutions for the design problems used in the experiments presented in this thesis, we applied two different tactics. The solutions for the one of the problems, labelled “Ball”, were classified into single solution categories, whereas for the other problems (see Table 5, page 41), a solution classification scheme based on problem decomposition was used. A classification scheme based on sub-functions was omitted for the Ball problem, because of the simple reason that solutions could be classified into a single class, and a more fine-grained solution analysis would not have served this purpose. Below are examples of solution classifications for the Ball problem. The categorization basis was a more detailed function employed to satisfy the super-ordinate function “transfer”.

TABLE 2. Examples of ideas for the Ball problem and their classification into solution categories.

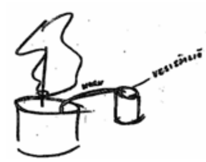
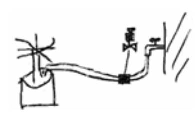
CLASS/DRAWINGS		
Free-moving collector (collect and deliver)		
		
Leveller (cause to roll)		
		

Alternatively, as said, the classification of the solutions for the other problems was based on decomposing the main function into primary sub-functions. To describe this classification procedure, consider the example sketches shown earlier (Figures 2 to 6) that represented solutions for the "Plant" problem. The description of the device should address the following sub-functions or questions:

1) Secure liquid for watering the plant;
2) Regulate the amount of watering (1 dl a week for one month);
3) Transfer secured liquid from the source to the plant;
4) Secure energy to operate the device.

Now, to satisfy these sub-functions, the designer needs to provide descriptions of particular structures that satisfy one or more of these sub-functions. If you consider the sketches shown earlier, they do depict a solution for each of these sub-functions that, to a large extent, are indeed separate sub-systems that can be, for instance, re-used in follow-up designs. The exception is that some solutions are passive or mechanic, and therefore, do not require any external energy source. Table 4 presents a breakdown of each of the ideas shown earlier (Figures 2 to 6) and corresponding sketches shown earlier into the four primary sub-functions shown above.

TABLE 3. Classification of ideas for the Plant problem based on a functional decomposition scheme. Each solution (i.e. idea sketch) is assessed and classified according to how it satisfies the following sub-functions (Sf): (1) Secure liquid for watering the plant; (2) Regulate the amount of watering; (3) Transfer secured liquid from the source to the plant; (4) Secure energy to operate the device.

IDEA NUMBER	SUB-FUNCTION	CLASS	DRAWING
Idea # 1	Sf1	Separate Tank	
	Sf2	Mould humidity - automatic	
	Sf3	Absorbed – through object	
	Sf4	“Not needed”	
Idea # 2	Sf1	Water-pipe	
	Sf2	Timer	
	Sf3	Drained	
	Sf4	“Not needed”	
Idea # 3	Sf1	Separate tank	
	Sf2	Steady flow	
	Sf3	Pumped	
	Sf4	Preliminary adjustment	
Idea # 4	Sf1	Separate tank	
	Sf2	Mail delivery	
	Sf3	Pumped	
	Sf4	Organic life-form	
Idea # 5	Sf1	Integrated tank	
	Sf2	“Not defined”	
	Sf3	Vaporized – active	
	Sf4	“Not defined”	

In addition to productivity assessment, categorization enables doing some further assessments. Categorization makes it possible to compare similarities across subjects’ creations, despite differences in detailed solution attributes.

Furthermore, an assessment of the categorical distribution of the total idea pool allows assigning frequency indices for single categories. These indices can then be used to determine, for instance, the categorical novelty of single ideas. This type of assessment was used in one of the experiments, to compare how time-elapse influenced whether subjects sampled ideas from common or novel categories.

There are a few shortcomings to assigning a variety score based on a functional-decomposition scheme. The assessment does not consider the completeness of the original pre-inventive structure that forms the basis of a finalized idea, i.e. the measurement technique does not differentiate between whether a subject generated an idea based on a relatively complete model, or assembled it from multiple sources (see pages 15-17). On the other hand, it is unlikely that one could reliably estimate the actual sources of ideas and their pre-inventive completeness in ways required for a rigid assessment. Thus, the variety score gives only an indirect estimate of the amount of knowledge structures sampled during idea generation.

3 RELATED STUDIES

The characteristics of idea generation in engineering design were presented in the previous chapter. In this chapter, I will review relevant earlier studies that have used a comparable setting to the study of creative thinking in engineering design and other disciplines. This chapter begins with discussing a theory of Creative cognition called Structured imagination (Ward 1994, 1995) and reviewing empirical studies performed to support its premises. Then, relevant empirical studies and findings on exposure effects in generative tasks are considered, since exposure effects are the main focus of the empirical part of this thesis. Last, studies that deal with the process and performance differences between individuals and groups are reviewed and discussed, since direct and indirect effects of idea exposure are influential in regards to group performance.

3.1 STRUCTURED IMAGINATION

If subjects would respond to creative drawing tasks randomly, without any similarities across subjects, idea generation would not be within the scope of most cognitive theory. In this case, we would have to admit to the fact that differences in creative thinking tasks would be explained almost entirely by personal traits and styles that are beyond the scope of this study and controlled experimentation. Fortunately, as it turns out, imagination used for creative thinking seems to be heavily structured by the way knowledge is organized, accessed, and exploited. The Creative cognition approach (Finke et al. 1992) provides valuable insights to the study of idea generation. Marsh et al. (1996) captured the significance of this initiative as follows "…once viewed entirely as an individual difference, creativity is now known to be supported by very regular, universal, cognitive processes."

A relevant theory stemming from Creative cognition is Ward's (1994, 1995) theory Structured imagination. The basic proposition of Structured Imagination is that "…when people use their imagination to develop new ideas, those ideas are heavily structured in predictable ways by the properties of existing categories and concepts (1995, p.157)". Ward uses the general principles of categorization to explain imaginative thought involved in generative tasks. His theory commences from the notion that people organize knowledge into categories, in which knowledge is organised hierarchically (e.g. Rosch et al. 1976). According to Ward, subjects start out by bringing into mind a category exemplar or some other strongly correlated image, and then explore this image and adapt it to possess novel attributes. Ward extends his theory to include the Path of Least Resistance model, which states that subjects will first present responses that are most active, and as a result, easiest to access. This model seems especially valid in the context of creative generation, and, if the assumptions are correct, it would have significant implications on several aspects of idea generation. For instance, according to this model, initial creations would occur similar over subjects with compatible task-knowledge, and consequently, those creations would have low novelty in statistical terms.

To find empirical support for his theory, Ward (1994) asked subjects to generate instances of creatures inhabiting a planet in space. He hypothesized that subjects would base their space creatures on the properties of related well-established concepts, such as, earth animals. The experimental logic of the first experiment was that if subjects' creations are structured on the basis of salient properties of existing categories, then subjects' initially imagined creatures should contain characteristics that are most common to members of familiar concepts. Ward used attribute-listing data (i.e. subjects are asked to write down attributes of common concepts; Barsalou, 1985), which is thought to present beliefs about attributes that are shared by category members, from prior experiments as basis for assessing the degree to which subjects conform to salient properties of existing concepts. The basic finding was indeed that the majority of the generated space animals had properties, which were characteristic of known concepts (e.g. humans and animals). Ward and colleagues have extended these findings also to other conceptual domains, including tools and fruit (Ward et al. 2002). Figure 7 presents examples of imaginary creatures generated in Ward's seminal study (1994). The experiment showed that some of the features present in the examples given in figure 7, were present in the majority of the imagined creatures, for instance, 89 % had eyes, 78 % had legs, 59 % had a nose (data calculated from Ward 1994, Table 2).

FIGURE 7. Examples of imaginative creatures inhabiting a planet in space (adapted from Ward 1994).

There is however a significant distinction between tasks in which subjects are asked to generate novel instances of *well-established* categories (e.g. animals) and the novel design problems devised for our study, which were designed to include devices that the subjects had not confronted earlier. In other words, we would assume that the design problems we have used here are unfamiliar to designers to an extent that they do not begin with category exemplars, simply because there are not any. On the other hand, since this work deals with a specialized task domain, and focuses on subjects that are educated within that discipline, we would assume some regular responses to emerge within subjects' ideas. A related claim in engineering design is that subjects would use earlier solutions as models for patterning new creations (e.g. Lawson 1997, Ward et al. 2000). While this aspect has not been directly experimented before in engineering design, Ward's theories implicate that such findings would occur.

3.2 EXPOSURE EFFECTS

3.2.1 Stimulation

Social psychologists have recently shown that other's ideas can positively influence one's ability to produce ideas through cognitive stimulation (e.g. Brown et al. 1998, Hinsz et al. 1997, Nijstad 2000, Paulus and Yang 2000, Coskun et al. 2000, Dugosh et al. 2000, Nijstad et al. 2002, Dugosh and Paulus

2005). The mechanism for cognitive stimulation is that other's ideas serve as cues that can help to retain task-relevant knowledge that would have been inaccessible in the case such triggers were absent. The theory behind cognitive stimulation is based on the notion of an associative memory network (e.g. Collins and Loftus 1975, Raajimakers and Shiffrin 1981, Anderson 1983). The basic proposition is that ideas are linked to each other in semantic networks, and once an idea is activated it further spreads activation to other ideas with related attributes.

Brown et al. (1998) considered the impact of other's ideas in a brainstorming influence model, which was intended to simulate how various variables affect the group idea generation process. The basic representation was a matrix model for between/within category transitions. The model is depicted in Figure 8. Each entry presents the probability that, given an idea from a certain category, the brainstormer will generate an idea from another category or the same category. Thus, two transitions – between and within – categories are possible. The transition probabilities are a function of the associative strength between and within the relevant categories. Within category transitions were thought to be more probable than between category transitions. Nijstad (2000) designed a related model, called Search of Ideas in Associative Memory. Nijstad assumed that idea generation was a two-step process, in which an item retrieval phase is followed by an idea production stage. The arrangement is rather similar to that of the Geneplore model (Finke et al. 1992).

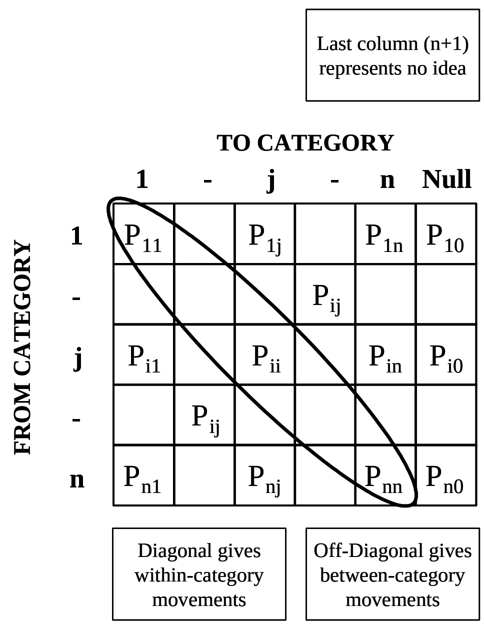


FIGURE 8. The Matrix model (adapted from Brown et al. 1998).

Several laboratory studies have been performed to study the impact of stimulus ideas on idea generation performance. Paulus and Yang (2000) compared the performance of groups that were able to share ideas on written notes to nominal groups (a group of individuals work alone without interaction), and found that idea sharing increased idea productivity. They believed the results were a result of cognitive stimulation. Dugosh et al. (2000) performed a series of three experiments to test the extent to which stimulus ideas facilitated idea production. The general finding was that ideas do indeed stimulate the production of ideas, but only in cases that subjects are asked to memorize the ideas, which is thought to be an indirect measure of the care with which persons attend to the ideas that are given as external stimulus. Interestingly, in this study, productivity gains were proportional to the number of ideas exposed, signifying that the more ideas are shown the more a person may become stimulated. Coskun et al. (2000) reported two more experiments in which category labels were used as stimulus. They included a manipulation of the sequence and timing of exposure, and found that number of category labels shown was positively correlated with performance, whereas the manipulation of the presentation sequence gave mixed results. Nijstad et al. (2003) performed a further study in which they manipulated the contents and sequence of the stimulus ideas. The finding was that subjects who were exposed to heterogeneous stimulus surveyed ideas from more categories than those that were homogenous ideas. Finally, in a similar exposure setting, Dugosh and Paulus (2005) manipulated the commonality and number of exposure, and found most stimulation with a large number of common ideas.

Taken together, the studies have shown that under some circumstances idea exposure can increase ideational fluency in terms of number of ideas generated. However, the studies have also shown that stimulation occurs mostly within categories and thereby does not increase the flexibility of idea production (e.g. Nijstad et al. 2003). Even more, subjects receiving access to other's ideas have been shown to survey fewer categories in comparison to their counterparts that receive no stimulus ideas (Larey and Paulus 1999, Ziegler et al. 2000). In fact, this effect is compatible to a negative effect known as design fixation that has been observed in design idea generation (e.g. Jansson and Smith 1991). The term fixation in an exposure context usually refers to conformity effects that result from exposure to examples before idea generation, which reduces the flexibility of idea production (see next sections). Apart from fixation, examples may also interfere through other means. For instance, idea sharing causes competing demands between listening to other's ideas and generating one's own ideas. Secondly, according to Nijstad et al. (2002), ideas are activated in semantic clusters, and stimulus ideas can disrupt a train-of-thought, resulting from abandoning a given category from which the subject could have generated ideas with high fluency. In summary, stimulus ideas may have a positive (cognitive stimulation) and a negative (interference) effect on performance in idea generation, and this effect may cause varying effects on different performance measures. In the next section, the concept of fixation is discussed, since fixation is generally thought to be a significant hindrance to solving design problems productively.

3.2.2 Fixation - insight problem solving

The concept of fixation was introduced by the Gestalt psychologists in the 1930s (Maier 1931) to explain why subjects had difficulty in solving problems for which they had the required skills and knowledge. Fixation is a cognitive memory phenomenon related to interfering effects of prior knowledge. Fixation may result from the way that knowledge is organized in long-term memory (internal causes) or from situationally induced external priming (external causes). Fixation effects are traditionally studied in the context of solving insight problems. Insight problems are well-defined problems, which include single solutions that tend to occur by a ‘moment of insight’ after initial unsuccessful attempts to solve the problem. A characteristic solution pattern in insight problem solving is that initial solution attempts end up in an impasse, and further work on the task, or time off (Smith and Blankenship 1991), will result in a sudden revelation of the solution (Knoblich et al. 2001). The patterns that may cause the impasse are the general forms in which fixation may occur. Three general patterns of fixation are typically acknowledged: functional fixedness (Dunckner 1931), entrenched mental set (Luchins 1942), and memory blocking (Smith 1995). The pattern that causes the impasse for a given situation depends on the type of insight problem (Knoblich et al. 2001). Traditional insight problems include: two-string problem, Remote Associates Test (RAT) problem, and water-jar problem. These three problems are used next to describe the different forms in which fixation may occur.

Fixation was initially thought to be related to the way that a person is ‘fixated’ by the common functional properties of objects (Dunckner 1931). A typical problem is the two-string problem. In this task, a subject is asked to tie two hanging strings together although he cannot reach them in arms-length. The subject receives also pliers that can be used to help to tie the strings together. The solution does not include using the pliers to simply grasp (i.e. ordinary use of pliers) the strings in any way. Instead, the pliers need to be tied to one of the strings and swung like a pendulum (i.e. novel use of pliers), while holding the other of the two strings by hand. This will allow the subject to reach both of the strings and finally tie them together. This is what is called *functional fixedness*, referring to the way that the use of an object is limited to its intended function.

The second pattern causing an impasse is called Einstellung or mental set (Luchins 1942, Luchins and Luchins 1959). Mental set refers to learning a routine representation of a problem, when the routine representation does not lead to the correct solution, an impasse occurs. A classic example to explain Einstellung is the water-jar problem (Table 3). The arrangement for the water jar problem is that a subject has three various sized containers and an unlimited supply of water, and he is asked to attain a certain amount of water. To cause an Einstellung, the problems are organized so that several consecutive problems (Problems 1-5 in Table 3) can be solved with a simple rule (fill biggest jar and reduce amount of water by filling both of the smaller ones). Now, a further problem (6, in Table 3) cannot be solved with this rule and the subject ends up in an impasse i.e. he cannot figure out a new measuring sequence to attain the required amount of water, because his thinking is ‘mechanized’ through the repetition of a particular rule. This type of fixation is called mental set..

TABLE 4. An example of inducing an Einstellung or mental set in the Water Jar problem. The objective is to attain a required amount of water from an unlimited water supply by using three various sized water jars.

	JAR 1	JAR 2	JAR 3	AMOUNT REQUIRED
Problem 1	142	12	44	86
Problem 2	23	87	33	31
Problem 3	59	133	8	66
Problem 4	91	66	11	14
Problem 5	8	42	74	24
*Problem 6**	13	27	115	48

*) To solve the problem reduce two small and one medium jar of water from the largest jar to obtain the correct amount of water.

A third cause of fixation was introduced by Smith (1995). Smith depicted that fixation can occur as a memory block, due to simple response competition. Smith (1995) has used Mednick's (1962) Remote Associates Test (RAT) problem to demonstrate memory blocking. RAT problems include associating three words with a single correct word. One particular test used by Smith is to associate words house-apple-family with a related word. If one happens to think of the word "green", he or she will probably end up in an impasse; the retrieval process gets stuck because the negative prime adds more activation to the incorrect solution (the correct solution is "tree"). This type of fixation is called memory blocking or mental rut.

All of the three types of fixation have been shown to interfere with problem solving. Experimental evidence on fixation has been gathered by exposing half of experimental subjects to negative primes and comparing their performance to a control group. A recurring finding is that task-completion times are longer for the negatively primed group (e.g. Adamson 1952, Adamson and Taylor 1954). An important implication of this notion, apart from the fact that fixation does occur, is that the majority of negatively primed subjects tend to eventually find the correct solution, signifying that fixation imposes only temporary obstacles to problem solving.

3.2.3 Fixation - generative tasks

Negative transfer effects have also been studied in the context of design idea generation and other generative tasks. Jansson and Smith (1991) were first to present an experimental approach to the study of fixation in the design process. They studied an arrangement in which half of experimental subjects were given a pictorial example before idea generation, whereas the other half performed the task without such stimulus. The finding was that example features, classified as similar to those in the examples, remained at an abnormal rate in the subsequent designs of the exposure group, i.e. subjects “conformed” to the examples. To generalize the findings and avoid bias to a single design problem, Jansson and Smith (1991) replicated this experiment with four different design problems, and found significant evidence of conformity effects across the design problems. Furthermore, conformity effects occurred also for experienced designers and with an example that included features that were in conflict with the design requirements. Similar findings were reported by Purcell and Gero (1992), Purcell et al. (1993), Purcell and Gero (1996), and Chrysikou and Weisberg (2005). The testimony that fixation does occur in design is quite convincing, and as a result, design researchers generally acknowledge design fixation as a significant hindrance to design idea generation, which limits the diversity and originality of subsequent idea generation.

However, Purcell and Gero (1992) and Purcell et al. (1993) did show that fixation effects may only occur with specific examples; they suggested that fixation effects may be prevalent only with examples that contain typical principles of the subject’s domain (Purcell et al. 1992). Figure 9 shows two example designs of which only the other (on the left side) caused fixating effects for mechanical engineering students.

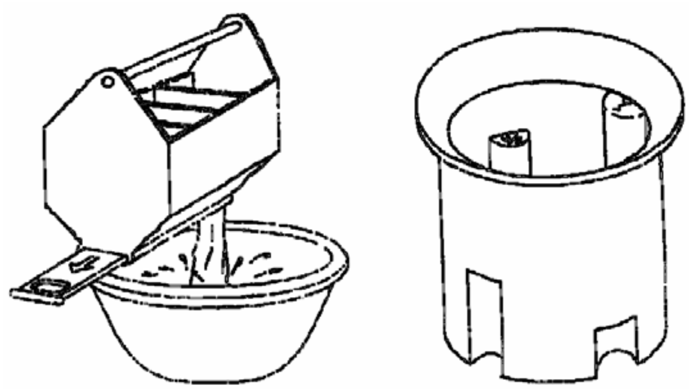


FIGURE 9. Example designs for a measuring cup for the blind. Purcell et al. (1993)

Exposure effects have been studied also in the context of more open-ended generative tasks. Smith et al. (1993) presented a series of three experiments, in which they asked subjects to generate novel instances of toys and animals, while exposing some subjects to examples prior to idea generation. Three example designs, with similar critical features (e.g. all three example space creatures had four legs, an antenna and a tail), were given to an exposure group, and the prevalence of these features in generated space creatures and toy designs was compared to control subjects' creations. The results were straightforward: significant conformity effects were found in all experiments for most of the critical features present in the examples. One of the experiments included a 23-minute delay between example exposure and generation, and another, instructions to avoid reproducing the examples, but these manipulations did not decrease conformity with examples.

Marsh et al. (1996) extended the findings of Smith et al. (1993) in two follow-up experiments, using the space creature task. In the first experiment, they manipulated the number of examples (0, 1, 3, 6, 9) that were shown to subjects. All examples, independent of the number, had the critical features (four legs, antenna, and eyes) in common. The finding was that conformity increased as a function of the number of examples. The second experiment was meant to align example effects with a specific rule of general categorization, namely correlated attributes (i.e. particular attributes tend to co-occur, e.g. wings and feathers), this effect was also evaluated by Ward (1994, Experiment 2) in a non-exposure context. The finding was that conformity occurred also for falsely correlated attributes, which signifies that the detrimental effects of examples overrule even general principles of categorisation. Finally, Marsh et al. (1999) performed a series of experiments to evaluate whether conformity effects would occur also for non-typical attributes. The first experiment included showing subjects three examples with features related to the concept of “hostility” (all examples creatures had fangs, spikes, and weapons). The finding was that the hostile features were more prevalent in the exposure subjects’ creatures in comparison to those generated in the control group. In this series, they also included a manipulation of the mind-set of respondents, and, in fact, noticed that an artificially-induced hostile mind-set (induced without examples), made subjects imagine creatures with features related to the concept of hostility more often than their counterparts.

Smith et al. (1993) first reasoned that conformity effects were a result of the simple fact that subjects may assume that they should conform to examples, when they are present. However, when conformity was explicitly requested, conformity further increased, which suggests that the subjects were not deliberately conforming to the examples before instructions to do so were made explicit. Based on this finding and the observation that conformity occurred also for example features that were in conflict with problem description (e.g. Jansson and Smith 1991), several authors concur to the perspective that conformity effects are unintentional or unconscious to a large extent (e.g. Smith et al. 1993, Finke 1996, Chrysikou and Weisberg 2005). Moreover, conformity effects usually occur even when explicit instructions to avoid reproduction are given (e.g. Smith et al. 1993, Marsh et al. 1996, Marsh et al. 1999, see also Ward and Sifonis 1997), which further strengthens this conception An exception was the study by Chrysikou and Weisberg (2005) in which the instructions were specific on the exact features that were to be avoided. Furthermore, Landau et al. (2002) were able to reduce example conformity when they told subjects that a plagiarism expert would review their creations to determine whether they had used features from the examples.

In summary, all of the experiments reviewed above seem to concur to the hypothesis that examples constrain performance in generative tasks, whether subjects are generating imaginary creatures or solving design problems, so that subjects unconsciously conform to features represented in the examples.

3.3 INDIVIDUAL VS. GROUP PERFORMANCE

Idea sharing is a central process in group idea generation (Paulus and Yang 2000). Therefore, the effects of idea exposure are a relevant issue in research that deals with group interaction and performance. Osborn (1957), who invented the well-known group technique – Brainstorming – proposed that other's ideas should stimulate or facilitate idea production. And indeed, as shown in the idea exposure studies (see pages 31-34), this proposition seems to be correct at least under certain conditions. Brainstorming is based on applying a set of four rules while generating ideas in a group: no criticism, emphasize quantity, think of uncommon ideas, and build upon other's ideas. The excitement around brainstorming, that begun some fifty years ago, has also led to the establishment of a body of empirical research, mostly from social sciences, sometimes called the "Brainstorming literature", which mostly deals with performance differences between groups and individuals. The recurring finding from these studies is that, even with the positive impact of cognitive stimulation, interactive groups have been systematically shown to produce fewer ideas than the same number of individuals working alone. This finding has been replicated in a significant number of independent studies (for reviews see Lamm and Trommsdorff 1973, Diehl and Stroebe 1987, Mullen et al. 1991).

The established explanation for the performance difference between individuals and interactive groups, or "productivity loss of brainstorming groups", is that group interaction imposes some mechanical (production blocking) and social inhibitory processes (evaluation apprehension, free-riding, and downward performance matching) that seem to generally weaken the performance of a group below the baseline level of a respective number of individuals. It is widely acknowledged that these factors start to affect groups of three persons and thereon increase as a function of group size. Figure 10 presents a caricature of an ineffective brainstorming session, the illustration is meant to capture the widely cited factors that make interactive group-work rather inefficient (commentary is given below).

FIGURE 10. A caricature of a brainstorming session.

Production blocking refers to the fact that when ideas are generated in a group, persons must wait for their turns to express ideas. In the figure, the person in the upper left-corner is speaking (or presenting his ideas), and is therefore blocking others from contributing. Additionally, while others are attending to his ideas and thoughts, they are not able to generate their own ideas. Therefore, production blocking also interferes, or even disrupts, further generative thought (e.g. Nijstad et al. 2003). *Evaluation apprehension* operates so that participants may be unwilling to state some of their ideas, since they fear to be negatively evaluated or ridiculed by other group members. The person who is speaking in the illustration may be an executive, and therefore, others may avoid presenting further ideas that seem silly or inappropriate in the current context. A third hindrance is *free riding*, also referred to as *social loafing*, which refers to the notion that some participants may not contribute to the idea pool, since they feel that their effort is not needed. In the picture, the person in the lower left-corner is backed away from the table, and therefore, does not actively participate in idea production. The fourth factor is *downward performance matching*, referring to conforming to low performance norms. It should however be noted that performance matching may occur also upward, when subjects are exposed to high-performing individuals, or when the group context induces a sense of competition that increases motivation to perform well in the task (e.g. Paulus and Dzindzolet 1993, Paulus et al. 1993, Munkes and Diehl 2003).

To compensate these difficulties, researchers have begun to develop procedural techniques, based on process structuring (e.g. Dennis et al. 1996, Brown and

Paulus 2002) and group support systems (e.g. Fjermestad and Hiltz 1998, DeRosa et al., in press), that possibly overrule commonly cited difficulties, while maintaining the positive aspects of group interaction (e.g. cognitive and social facilitation). Although some benefits have been reported through the use of e.g. electronic idea sharing tools, these systems do not support other presentation formats than textual, and therefore are not applicable to engineering design, given the fact that designers prefer to visualize their ideas in the form of sketches.

3.4 SYNTHESIS AND FURTHER QUESTIONS

The demonstrations for negative exposure effects, i.e. conformity with examples, are quite convincing for design idea generation (Jansson and Smith 1991, Purcell et al. 1991, Purcell et al. 1992, Purcell et al. 1993, Chrysikou and Weisberg 2005) and other generative drawing tasks (Smith et al. 1993, Marsh et al. 1996, Marsh et al. 1999). However, theories of cognitive stimulation (Brown et al. 1998, Nijstad 2000) expect that idea exposure should, in fact, stimulate the production of further ideas, which opposes the view that examples cause only harmful effects on idea generation performance. Indeed, idea exposure has been shown to increase productivity in verbal open-ended idea generation (e.g. Paulus and Yang 2000, Coskun et al. 2000, Dugosh et al. 2000, Nijstad et al. 2002, Dugosh and Paulus 2005). Thus, the theory surrounding exposure effects in idea generation has converged into a dual influence model, in which, both – negative (cognitive interference) and positive (cognitive stimulation) - effects are anticipated.

There are several further important avenues of investigation that could unravel exposure effects in greater depth. The notion stemming from, for instance, the work of Nijstad et al. (2003), is the proposition that through manipulating the sequence, quantity, and contents of exposure, externally imposed ideas could result in varying effects on performance. Secondly, the issue that has yet to be discovered is what influence examples have on different performance measures. Hence, to this date, exposure effects on performance have been almost single-handedly assessed through a simple count of generated ideas. A further, and perhaps more relevant, performance aspect would be the effect that examples have on the diversity of idea generation, which can be assessed by the classification technique shown here (see pages 24-28). Thirdly, there are possibly substantial differences between different task-domains in terms how examples affect idea generation, this statement is justified e.g. by the two apparently opposing views between findings and implications from design research and social psychology, i.e. design theorists seem to generally concur to the perspective that examples only interfere with idea generation, while psychologists propose that examples (or other's ideas) generally stimulate idea generation. Finally, there are conflicting theories underlying what mechanisms cause fixation effects in generative tasks (see e.g. Purcell and Gero 1996, Marsh et al. 1996). Indeed, this issue has yet to be resolved theoretically, and therefore, it is quite difficult to come up with schemes that overrule fixation and leverage the stimulation value of external representations. Therefore, much empirical and theoretical work remains to unravel the apparent complexity of exposure effects in idea generation. Nonetheless, a careful assessment of effects of idea exchange (or exposure) could lead to knowledge that can be employed to develop better procedures for group idea generation.

4 SUMMARY OF PUBLICATIONS

Overview

Responses from 228 students are reported in the experiments included in this dissertation. The majority (75 %) of these subjects were mechanical engineering students at the Department of Mechanical Engineering in Helsinki University of Technology. The average age of respondents was 24 (SD = 2) years. The average curriculum phase was 114 (SD = 30) study credits completed from a minimum total of 180 study credits required for a master's degree. 56 % of the subjects had more than half a year of design experience in practice. 90 % of the subjects were male.

In each of the experiments, subjects generated ideas for a single design problem under a pre-fixed time limit. The duration of the sessions ranged from 20 to 45 minutes. Five design problems were designed by the Navigo team for the purpose of the research project: a ball moving device, a food packaging system, an automatic watering device for house plants; a beverage cup holder; and a demolisher of tree-trunks. These tasks are labelled and described in Table 5.

TABLE 5. Task labels and descriptions for five design problems used for experimentation purposes in the Navigo project.

TASK	DESCRIPTION
Ball	An automatic device that transfers balls from a playing field to a goal-area.
Plant	An automatic watering device for houseplants that provides a plant with a decilitre of water per week for a total of one month.
Package	An automatic collection-system that moves food-packages from full boxes composed of single items, into customer boxes with mixed food packages.
Beverage	A cup-holder for transporting a beverage container in a car within the reach of the driver.
Tree	A human-controlled walking device that demolishes tree-stumps on site in a harvesting area.

Subjects worked individually in all of the experiments. The performance data was gathered from the externalized output that were in the form of sketches (see pages 19-24). Two measures were primarily used to assess performance: the number of ideas and the number of categories surveyed (see pages 24-28). A standard answering sheet was used in all experiments. The answering sheet included separate frames in which to sketch single ideas. All ideas were requested to be presented as sketches, supported with textual annotations when found necessary. Subjects were requested to sketch the ideas so that the solution principles and main components were identifiable. We chose to use sketches as presentation format, since they serve the process of design better than other modes e.g. verbal or textual. Furthermore, sketches are common means of expression among the designer population, and thus a standard medium within real life idea generation sessions (e.g. Van der Lugt 2000, Vidal et al. 2004).

Publication I

This article included a design experiment that was designed to study whether idea exchange in real groups would promote idea production. The assumption was that idea exchange should increase idea productivity due to cognitive and social facilitation. The results of the study showed that although idea exchanging individuals generated more ideas, their performance was not enhanced in terms of the diversity of idea production. A further finding was that performance gains were of the same magnitude irrespective to the notion whether subjects exchanged ideas with one or three persons.

Publication II

The experiment presented in this paper was designed to discover effects of idea exposure on idea generation performance. Subjects were shown different types of example sets prior to generating ideas. The experiment was a 2 (number of examples: four, twelve) x 2 (commonality of examples: common, novel) factorial design. The results showed that positive design outcome, measured by the amount of new ideas that did not share resemblance with the examples, was correlated with the commonality of examples presented, whereas the amount of ideas presented did not have a significant impact on design outcome. Conformity effects were quantified by using a weighted measure of genealogical linkage between examples and generated ideas. The analysis showed that exposing subjects to common instead of unusual examples led to a higher genealogical linkage with examples.

Publication III

In this paper, two further design experiments were presented. The first experiment included monitoring subjects' idea generation performance in relation to time elapse. Performance was measured by assessing the number of ideas, the number of new categories surveyed, and the mean commonality of the surveyed new categories for three consecutive 15-minute intervals separately. The analyses showed that productivity declined as the session proceeded, whereas the categorical novelty of ideas increased respectively. The second experiment studied example exposure effects further. Subjects were shown differing example sets at different time-points in the session. The design was a 2 x 2 (interval: early 1-20 min, late 21-40 min) x 2 (commonality of examples: common, novel) x 2 (timing of exposure: before, after early interval) factorial design. Performance declination between the two intervals was found similarly as in the first experiment. The commonality manipulation did not cause significant changes on performance, whereas a considerable effect was found based on the timing of exposure. Subjects that were exposed to examples prior to the session surveyed significantly fewer new (i.e. non-redundant) categories than those that received the examples after twenty minutes had passed.

Publication IV

In the experiment presented in this paper, the effects of examples on process and performance aspects of design idea generation were further assessed. Verbal protocol analysis was employed as a research method to gather detailed data on how examples affect the idea generation process. Two experimental conditions were formed: one-half of the subjects were given four examples to be used during the task, whereas the other half performed the experiment without prior examples. The results of the study demonstrated that examples limit the diversity of output. On the other hand, the difference between linkage within ideas and categorical conformity with examples was non-significant between the two experimental conditions.

Publication V

A cognitive model of memory search in idea generation is presented in this paper. The model is called Cue-Based Memory Probing in Idea Generation (CuPRIG). The idea generation process was conceptualized to include three major phases: problem interpretation, image retrieval, and adaptation. Image retrieval from long-term memory to working memory was assumed to be a cue and context dependent process, governed by some function of the similarity between the elements of the search probe and target knowledge structures.

Publication VI

This paper presents an empirical test of the CuPRIG model. The experiment was designed to evaluate whether changes in contexts and cues affected the structure of generated ideas in a systematic way. Subjects were asked to generate design ideas after being forced an external cue or a particular environmental context. In one of two tasks there was a clear effect for contextual cueing; probabilities of generating ideas from particular categories changed in regards to the context in which the subjects imagined the design. The second element that was tested was the retrieval cue itself. Altering the cue with verbal manipulations led to the activation of a related semantic unit, which was then synthesized in a very straightforward manner to create a new idea. Despite some misalignment in the results, the findings were generally consistent with what could be estimated by the CuPRIG model.

5 RESULTS AND DISCUSSION

5.1 REVIEW OF EMPIRICAL FINDINGS

To begin discussing the main findings of this thesis, a logical starting-point is to view the consistencies in subjects' initial responses to the design problems in a free-form situation (i.e. no external stimulus other than problem statement). A seminal finding was that about half of the subjects first generated a highly similar idea in response to the design problems (Publication 2). This conformity between subjects is considerable evidence for the fact that subjects approach generative tasks in a highly consistent way. Similar conformity in initial responses has been observed in other generative tasks (e.g. Ward 1994, Ward et al. 2002). On the other hand, as the idea generation process unfolded, subjects moved on to generate ideas from more novel categories (Publication 3). However, the rate of idea production was shown to decrease simultaneously with increase in idea novelty (Publication 2; Publication 3).

The experimental part of the study focused also on the effects of idea exposure on idea generation performance. Recent theory and empirical evidence proposes that idea exposure may both stimulate and interfere with generative processes underlying idea generation. Four independent design experiments were designed to study exposure effects in design idea generation. The main findings from these studies were as follows. Performance was not affected by altering the amount of stimulus ideas presented (Publication 1 and 2). Transfer of principles or features from examples to subsequent ideas increased with the commonality of examples, so that common ideas led to a higher linkage with examples (Publication 2 and 4). Example exposure did not influence the number of ideas generated, but when examples were given prior to the session they degraded performance in terms of total variety of ideas (i.e. number of new categories surveyed) (Publication 3 and 4). No performance effects resulted from showing examples with highly novel sub-functional features in comparison to examples that were frequent in all aspects (Publication 3). Subjects did not generate more ideas from categories represented in the examples when the example set was heterogeneous in nature, i.e. examples did not cause significant conformity effects (Publication 4).

5.2 REFLECTION TO PRIOR RESEARCH AND THEORY

Researchers widely acknowledge that cognitive fixation is a general obstacle to creative problem-solving, which operates so that designers cannot think of alternative solutions once they have generated or been exposed to a solution, due to the inability of de-activating information. Indeed, several of the effects demonstrated here in design idea generation have been explained through the concept of fixation, including: categorical conformity between subjects' initial ideas (Ward 1994, Finke 1996), the declination in idea productivity over time (Howard-Jones and Murray 2003), reproduction of features from earlier ideas, and the decrease in diversity of ideas produced after being exposed to examples (e.g. Jansson and Smith 1991). On the other hand, there were several findings that contradict the occurrence of fixation. First, the increase in categorical novelty of ideas in relation to time-task is an opposite effect to design fixation (a positive time-related effect). Second, even that subjects built regularly on previous ideas, this behaviour was not more persistent when examples were shown. In addition, when subjects elaborated or combined earlier ideas, they made this intentionally, which was revealed by the fact that they made explicit verbal references to prior ideas that carried similar principles. Thus, there was no evidence that subjects unconsciously or involuntarily conformed to earlier ideas.

Despite the experimental demonstrations and intuitive appeal to explain time-related performance declination and negative influence of examples by the concept of fixation, I would argue that the subjects participating in our studies suffered very little from earlier generated/presented solutions in a sense that can be explained by the concept of fixation. Instead, I propose that these effects relate to the relative ease of generating ideas early in the session, and a difficulty of forming new associations as easily-accessible ideas are exhausted. This proposition may be explained from a memory search perspective in associationist terms as follows. When some ideas are initially strongly associated with the problem, subjects will first produce those strongly associated ideas because they are rather automatically accessed, and consequently they reach a high level of productivity at the beginning of the session. Now, to reach additional and more novel solutions, subjects must be able to evoke images that are initially weakly associated with the problem description. This will not be possible unless the activation of strongly-correlated ideas is relieved. Thus, the explanation given here is not that earlier solutions interfere with one's thinking processes per se, but that attaining additional knowledge structures (i.e. expanding the solution space) becomes relatively difficult after the initial strongly correlated images are exploited.

This theory is applicable to explain also why subjects who were exposed to examples before idea generation produced ideas from fewer new categories in comparison to control subjects (Publications 3 and 4). An intuitive interpretation of these findings would be that the subjects became fixated on the examples. However, if one considers the fact that a number of typical ideas emerged in the majority of responses, an evident trajectory occurs. Hence, the consequence of showing subjects examples, with a high probability of being generated also without exposure, is that exposure subjects' performance will be reduced in comparison to that of control subjects, as they miss the opportunity to add some of their 'own' ideas to the solution pool.

Nonetheless, the recurring finding from earlier exposure studies, which is that examples lead to significant conformity effects (e.g. Jansson and Smith 1991, Purcell and Gero 1992, Smith et al. 1993, Purcell et al. 1993, Purcell and Gero 1996, Marsh et al. 1996, Chrysikou and Weisberg 2005), cannot be explained by the proposition presented above. The main difference between our experiments and prior ones was that here we used heterogeneous example sets, whereas prior studies used single or homogenous examples. A probable explanation for the misalignment is that the subjects in earlier studies may have framed their perception of the problem space according to the uniform model represented in the example(s), even when the actual problem definition would have allowed alternative responses to be presented. This may have led the subjects to produce similar ideas to those in the examples, and importantly, also elaborate their ideas to a respective level of detail. In comparison, here we exposed subjects to varying representations and asked them to generate a large number of alternative ideas and present only the solution principle, and therefore they may have attained a somewhat broader and more economical view on the problem.

In regard to the often-cited stimulating impact of externally-induced examples (e.g. Dugosh et al. 2000, Paulus and Yang 2000, Nijstad et al. 2002, Dugosh and Paulus 2005), we were not able to find evidence for the notion that examples, i.e. stimulus ideas, significantly increased performance in terms of number of ideas generated, or any other dimensions. The conclusion is that examples do not stimulate the production of ideas above a base-line level, at least for design problems that are comparable to those used here. The misalignment between our design experiments and earlier ones from social psychology, that have shown increased productivity as a result of idea exposure, appears to be related to the differences between these two domains. A plausible explanation for this difference was given by Nijstad et al. (2002) who proposed that cognitive stimulation is likely to occur when there are many categories of solutions and many possible ideas per category. Such solution spaces are characteristic of open-ended tasks (e.g. list ways of improving your university), whereas solution spaces for design problems are much narrower. Even more importantly, solutions for design problems are *hierarchical*, which means that for any given principle solution a subject can produce an extensive amount of variation at lower abstraction levels with little or no effort. Hence, in the present experiments, subjects were asked to generate a large number of solutions and to visualize only the solution principle, they may have not considered important to elaborate the solutions in greater detail. Thus, it seems that cognitive stimulation occurs mostly within categories and only for idea generation tasks or topics that include flat solution spaces. It is unlikely that designers would become cognitively stimulated by examples or ideas of others so that their productivity would be significantly enhanced in comparison to a non-exposure mode.

5.3 MODEL OF THE PROCESS

The theoretical framework proposes that idea generation in design should be understood as a goal-oriented memory search process. A memory search model was formed based on this view founded on the theory of cue-based probing of context-dependent memory (Publications 5 and 6). The model is based on synthesis of a number of psychological theories of problem solving (Newell and Simon 1973), creative thinking (Finke et al. 1992, Ward 1995), and memory retrieval (Raajimakers and Shiffrin 1981, Baddeley 1982, Thagard and Holoyak 1990, Brown et al. 1998, Nijstad 2000). The model, shown in Figure 11, includes three main phases: problem interpretation, memory search, and adaptation, as well as two decision gates.

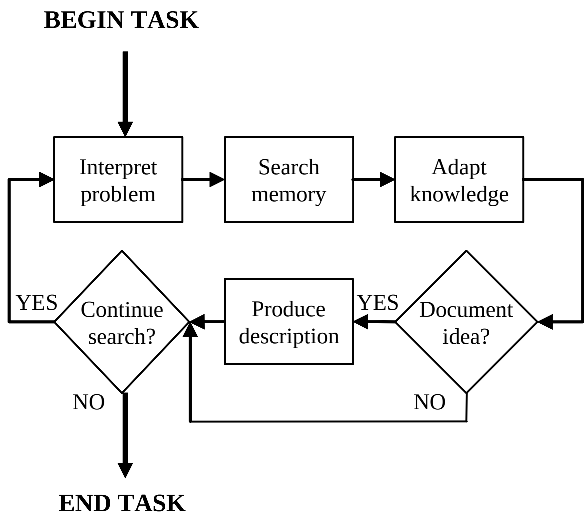


FIGURE 11. Model of the idea generation process.

The process of idea generation is outlined as follows.

1) Problem interpretation leads to establishing a mental problem representation, which often includes forming a problem decomposition scheme that is used to organize a sub-target oriented search process. The mental problem representation is formed on the basis of a subjective assessment of the objects of the problem environment, which are presented as nouns in a verbal problem description. After a mental problem representation is established, the subject moves on to search his memory for relevant knowledge.

2) Memory search is based on cue-dependent probing, in which the subject attempts to match a semantic query with task-relevant knowledge in long-term memory. This operation is governed by the similarity of the semantic attributes of the cue and corresponding features of one's knowledge structures. The direction of the retrieval cue is influenced by one's current problem representation, which corresponds to the independent and interactive contextual attributes of target structures. Memory retrieval results in the formation of a pre-inventive structure. Depending on the original attributes of the pre-inventive structure, it may take a conceptual or specific form.

3) In the adaptation process, the pre-inventive structure is transformed and explored in short-term or external memory with additional cognitive processes to meet the requirements of the current situation. The adaptation phase may also include integration of the retrieved structure to other system parts in case it represents only a partial solution.

4) After successfully retrieving and adapting knowledge to form an idea, the subject makes two conscious decisions: whether to document the idea in external memory or discard it, and whether to continue or terminate the search task. In case the subject decides to search for further solutions, he needs to alter the semantic attributes of the search cue or change his problem representation in order to retrieve additional task-relevant knowledge.

5.4 LIMITATIONS AND FUTURE WORK

The study focused on the performance of a culturally-homogenous sample of design students engaging in idea generation in a simulated environment. We focused on a limited set of variables and did not consider the possible influence of factors related to e.g. motivation, personality, and expertise (see e.g. Amabile 1983). Whilst I see no justification to question the relevance of this focus area, it is appropriate to mention that several other external and internal variables are relevant for idea generation in practice. The studies reported here opened only a small window to the study of the idea generation process and substantial empirical research is further needed to unravel the mutual influences of components that play a role and affect performance in idea generation sessions. I do however claim that as the study processed the empirical data on a detailed level and was founded on a substantial body of research, the basic notions and findings do apply to, and are significant in the context of idea generation in engineering design.

In regard to the contribution of this work to applicable research methodology, I believe that the systematic empirical approach introduced and prototyped here is a powerful tool to gain insight on the thought processes involved in idea generation. That is, we isolated some relevant idea generation components, and performed a systematic theoretical and empirical evaluation of those variables by using objective measures and comparable procedures. Future studies could use a similar approach to explore, for instance, what modes of idea sharing/exposure leverage the positive influence of examples, while overruling negative exposure effects, through experimental studies that employ a diverse idea exposure paradigm. Although new empirical and theoretical insight was presented on this subject matter, it is premature to instruct how and when designers should share their ideas in idea generation meetings. Therefore, further studies are needed to gain knowledge on idea sharing modes that enhance the performance of idea generating groups from a combined perspective.

5.5 IMPLICATIONS FOR PRACTICE

This study was motivated by the notion that much we know about idea generation is based on intuitive belief systems rather than empirically validated theory. As a whole, I believe that this study provides a gateway for educators and practitioners to move beyond intuition, by understanding the cognitive mechanisms that underlie idea generation. As shown here, idea generation is not a random process governed solely by an individual's personal trait, but a relatively structured process that can be explained in terms of memory cognition.

The empirical findings reported here have implications for any context in which designers are influenced by past experiences or externally-induced solutions. Hence, the degree of past knowledge that an individual has with a given problem is highly influential in regard to his idea generation process. The basic mechanism of internal memory-based idea generation is an active search of images from one's repository of past experiences. In this view, proficiency in idea generation is determined by one's ability to activate a wide array of knowledge and adapt this information to meet the requirements of the current situation. Due to the limited capacity to keep information active simultaneously, the search process must be largely sequential, involving a cycle of activating and de-activating knowledge. The notion of predictability refers to the theory that for any image that is associated with a given design problem, there exists an associative strength, determining the probability of that image being activated. As shown, individuals may be able to generate several alternative ideas relatively quickly, in case a problem resembles previous ones and can thus be solved with prior experiences. However, this 'recognition-based' approach will result in the emergence of relatively common ideas. In pursuit of more novel solutions, individuals need to use their knowledge in a more imaginative way. This requires that individuals begin to process remote associations between the problem and past experiences. As a result of this shift in emphasis, solution search is slowed down. Therefore, it is important that individuals are persistent in their solution search, even if additional solutions become more difficult to find as a function of time-on-task.

A further remark that I wish to make is that by acknowledging the notion of a solution space, idea generation becomes more structured and manageable. Pursuing the sheer quantity of ideas is not necessarily a virtuous objective of an idea generation session. Instead, the extent to which a team is efficient in its solution search should be determined by the number of different principle solutions represented in the total idea pool. In this sense, single ideas should be considered as representatives of a category of solutions. Only after solution principles are abstracted from ideas and categorized accordingly, one is able to assess the extent to which a solution space is discovered. This arrangement highlights a further relevant issue, which is the difference between generating and elaborating ideas. Basically, if a subsequent idea is from the same category as its predecessor, the subject makes a within category transition, which means that he does not change the high-order principles, but focuses on more detailed aspects of the design. In other words, he spends time on elaborating an idea, and does not settle for the objective of expanding the abstract solution space. These notions should be attended to carefully, when instructing the way that individuals should approach a given idea generation task.

The work presented here dealing with exposure effects, questions the widely-held assumption that subjects become fixated on examples. Moreover, no significant evidence was found for the hypothesis that subjects become cognitively stimulated by the presence of examples so that their productivity is increased. Thus, from a purely cognitive perspective, examples seemed to have very little effect on total performance. The reason for not finding evidence of exposure effects may be that individuals exercise more conscious control over their idea generation process than has been previously implied. From this perspective, if prior solutions for a given design problem are known, those should be made available, as long as individuals are instructed to move away from the examples. This could even encourage individuals to approach the task from new perspectives, and deliberately orientate solution search efforts beyond the examples.

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