Visual materials and designers' cognitive activity: Towards in-depth investigations of design cognition

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Abstract: Since two decades, there has been a growing interest in design cognition and design creativity. Designing is often described as an informational process in which designers manipulate information to produce design outputs. In this informational processing activity, many studies pointed out the major role of visual materials. This paper reports a selection of lab-based experiments which investigated the role of visual information in the design process and its impact on design creativity. These investigations mainly focused the explicit process of design and today the implicit process still remains vaguely depicted. Based on both former design studies and findings on human brain processing, we propose further investigations on the perception of visual information in design activity and explorations of the link between visual information and design creativity. This paper shows a possible research direction where design science and cognitive science meet up with a common goal of better understanding design creativity.

Key words: Design cognition, design creativity, explicit and implicit process of design activity, analogical reasoning, visual perception, images, visual imagery

1. Introduction: Investigating design activity from various points of view

From the early works on design activity by [Simon, 1969], there has been a growing interest in studying design activity and design protocol [Cross et al., 1996]. Why such a growing interest? From the point of view of design educators and design practitioners, these studies help to enhance the design process and to improve the level of creativity of design outputs. Actually, knowledge of designers' practices and needs is necessary to propose new design tools or interfaces and to bring relevant information to designers. Studies on design activity are not only necessary for design process enhancements, they are also a perfect mean for discovering human brain capabilities. So far, very few cognitive studies focused specific professional activities; but design activity being such a complex combination of several cognitive operations (creativity, problem-solving, attention, visual perception, memory...), studying design cognition will increase the knowledge on human brain capabilities, especially creative capabilities. Besides, on top of design specialists and cognitive scientists, other connected fields can benefit from advances in design cognition, as artificial intelligence and computer science. Therefore, research on design cognition is useful for many disciplines.
As all human activities, design activity is made of two related components: implicit process and explicit process. The explicit process consists of using and creating visible components, while the implicit process consists of mental activities and mental computation of external information. So far, most design studies investigated the explicit design process, since it is more easily observed and assessed. But the more we want to refine the design activity understanding, the more we have to study implicit processes of design activity and the link between implicit and explicit processes. We recently noticed a growing number of studies on design implicit process; most of them consists in detecting differences in cognitive processes between novice and expert designers; in fact, after investigating the Limited Commitment Mode control strategy [Kim et al., 2007] or the problem decomposition strategy [Liikkanen & Perttula, 2008], the findings confirmed that the cognitive strategies of novices and experts were different. It also gives more knowledge about the problem-solving cognitive operation.

In this paper, we first introduced a selection design studies aimed at describing the explicit process of design activity (section 2). Then, we report an overview of studies which help understanding the design process; these studies are mainly investigating creativity and analogical reasoning in design. In this context, our focus is the role of visual information in design creativity, about which we report some initial experiments. To push these investigations further, we propose to carry out in-depth investigations correlating design tangible traces and designers' brain activity. In other words, our objective is to study the relationship between the explicit and implicit processes of design activity.

2. Investigating the explicit process of design activity

In this paragraph, the most studied components of design activity are reported: sketching, browsing visual materials, reasoning by analogies. At the end of this section, we propose a representation of design activity, emphasizing the relationships between the explicit process and the implicit process of design.

2.1 Sketching activity: producing hand-made drawings

Sketching is an important part of design practice and design education and there has been a large amount of research investigations on the sketching activity by designers. As [Schön, 1992] defined it, design can be seen as a reflective conversation based on a generation-visualization loop, made possible by the production of hand-made drawings. Based on observations of the usual practice of sketching, it was confirmed by later studies that sketching would enable to designers to visualize and interpret their ideas and the visualization of their own sketches would give a new twist to their idea flow [Van der Lugt, 2001] [Tovey, 2003]. Designers externalize their mental images by sketching. Sketching is essential in design process not only because it supports the generation of new ideas, but also because it prevents designers to experience an overload of visuo-spatial working memory [Bilda & Gero, 2007]. In an experiment with six architects, the authors compared the design process in blindfolded and in sketching conditions. An interesting finding is that overall cognitive activity and perceptual activity in blindfolded conditions drop below the activity in sketching conditions after 20 minutes during the timeline of design activity. An explanation proposed by the authors is that blindfolded condition requires a higher cognitive activity and that when not sketching, designers will experience overload of visuo-spatial working memory. It was also observed that in blindfolded conditions, the idea generation index significantly dropped in the second periods of blindfolded sessions but not in sketching session. This reinforces the idea that sketching activity impacts idea generation and thus is crucial in the design process.

2.2 Browsing activity: looking at inspirational visual information

In the design process, visual information are a major support for analogy-making. Two famous examples are
quoted in research literature: “Juicy Salif” lemon squeezer would have been inspired by sci-fi comics books read by Philippe Starck as a young boy [Lloyd & Snelders, 2003] and The Dancing Building in Prag, designed by Frank O. Gehry from a movie dancing scene with Fred Astaire and Ginger Rogers [Kacher, 2005].

Aside these famous examples of visual inspiration, it has been frequently observed by researchers that designers intensively browse images from magazines or websites and used collection of precedents. To support this common practice among designers, design-dedicated softwares or interfaces have been developed to retrieve images, such as : EVIDII and IAM-eMMa [Nakakoji], ProductWorld [Pasman, 2003], Cabinet [Keller et al., 2005, 2009], CRAI Interface [Kacher, 2006], i-vidi [Jung et al., 2007], TRENDS [Bouchard et al., 2008].

<table>
<thead>
<tr>
<th>ProductWorld</th>
<th>Similarity-based Engine</th>
<th>Cabinet</th>
<th>TRENDS</th>
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<tr>
<td>[Pasman, 2003]</td>
<td>[Restrepo, 2005]</td>
<td>[Keller et al., 2005, 2008]</td>
<td>[Bouchard et al., 2008]</td>
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It is widely recognized that designers collect images and use them to prepare graphic display, such as trendboards for instance. An on-going study [Kim et al., 2008] aim at describing the intermediate step between images collection and sketching, also called “information categorization”. In this step, design information get externalized by sketching activity, it relates to cognitive tasks of construction, categorization and application of design information for idea generation.

2.3 Design thinking: analogical reasoning and visual imagery

Design process is largely based on cognitive operations of problem-solving, as association of ideas: combination, mutation, analogy [Rosenman & Gero, 2002]. In a study with four architectural designers who had to describe verbally their mental path, [Leclercq & Heylighen, 2002] observed that 5.8 analogies/hour were made. Research in psychology is much interested in problem-solving issues and many studies have been trying to model creativity processes. In fact, we learn from a psychological literature review by [Anolli et al., 2001] that analogical-reasoning consists of two key steps: “retrieval” (alternatively called retrieval, search, selection or access) during which designers evoke potentially-inspirational information, and “mapping” (alternatively called use, applying or adapting) in which designers adapt selected information to the design target. Their study with a panel of students (non-designers) showed that analogical reasoning is improved when the subjects are prompted to use designated sources of information. Even though designers might have better creative abilities than the normal population, we tend to think that helping designers to retrieve relevant sources of information will support their analogical-reasoning and creative activity; this might be particularly helpful for novice designers.
Transforming keywords into visual images is a common operation processed by designers, which was studied by [Nagai & Noguchi, 2002]. The focus was about the way designers think with drawings in order to generate visual images of an artefact. In doing so, designers have to link low-level information (drawings, artefact) with high-level information (abstract keywords) and thus, the creative thinking process needs an overall high abstract level when having to create a visual image from a verbal stimulus. The transformation of a verbal stimulus into visual imagery can be seen as a specificity of design practice.

2.4 A representation of design cognitive activity

To summarize the above-referenced studies, we attempted to represent the design process as a flow of information, involving cognitive operations, as shown in figure 1 below. Along a design activity timeline, this process is made of steps from the reception of a design brief to the production of sketches. This process consists of two major components:

1) emergence: retrieval and mapping steps, ending up with the generation of an idea
2) sketching: generation-visualization iterative process / ideas refinement through the production of drawings

![Fig. 1: Implicit and explicit processes of design activity, with a focus on the use of visual information [Mougenot, 2008]](image)

The time when each cognitive operation occurs still has to be clarified, but this model is mainly aimed at gathering designers' cognitive operations in one single view, showing that implicit and explicit processes are connected and that external visual information play an essential and continuous role in design creativity.

3. Investigating the role of visual information in the design process

3.1 Images and their impact onto design creativity

A study by [Malaga, 2000] with a non-designers panel showed that images are a better source of creativity than words. The experiment objective was to compare the impact of picture and words onto creativity in a brainstorming task. Picture and word stimuli were used to elicit ideas. The results indicate that the use of picture stimuli outperforms words for generating creative ideas. Also an interesting finding is that pictures alone give better results than pictures and words combined.
In a design context, several other studies have demonstrated that images have a positive impact onto design creativity. For instance, [Christiaans, 1992] and [Leclercq & Heylighen, 2002] showed that the use of visual stimuli helped designers to produce more outputs; visual stimuli lead to the production of more ideas. Also, [Goldschmidt & Smolkov, 2006] compared the level of creativity of designers' outputs, in two different working environments: surrounded by pictures or not (fig.3). This study showed that visual stimuli not only help designers to produce more ideas but also they help designer to produce outputs with a higher level of creativity.

3.2 Noteworthy features of images used in design process

1) Distance between source and target

Analogical reasoning is defined as the retrieval of information from memory, followed by the mapping of selected retrieved information into a new context. In other words, inspirational sources can be gradually distant from the target. For instance, in a study by [Malaga, 2000], students from various backgrounds had to solve problems in various fields (medical sciences, politics...) with given clues from the same field ("close associates") or from other fields ("remote associates"). [Casakin & Goldschmidt, 1999] investigated how architects, students or experts, solved architectural cases, referring to architectural precedents ("within-domain") or to art, nature... ("between-domain"). In product design, according to [Bonnardel & Marmeche, 2005], inspirational sources can be assigned to three types of domain, based on the proportion of shared properties with the target: "intra-domain", "close inter-domain" and "far inter-domain", as quoted below:

- A source is judged as intra-domain if, without any ambiguity, it pertains to the ‘seat’ category, which is the category the object to be designed (target object) belongs to (e.g., a dental office chair, a rocking chair, etc.).
- A source is judged close inter-domain if it keeps some properties of the seat category but not the most prototypical ones (e.g., we can sit on a sledge or on a rocking horse, but there is no back as is the case for the most typical seat: a chair).
- A source is judged far inter-domain if it obviously does not belong to the category of the target object (e.g., a wave or a nest).

In the following table, we reported the terms used in design or psychological literature to describe the semantic fields involved in analogical-reasoning.
In the study by [Bonnardel & Marmeche, 2005], images were shown to designers who had to describe what element in the image was useful in the context of a given design problem. One of the findings was that inter-domain sources had a higher positive impact on the evocation of new ideas than intra-domain sources. Besides, depending on the domain of origin, the sources led to the evocation of different components: e.g. intra-domain sources mainly led to the evocation of functional aspects (rather than structural, affective or aesthetic aspects). In another study carried out with a sample of car designers, [Mougenot, 2008] observed that sources from other domains than car design, as architecture and fashion, had a positive impact onto the level of creativity of designers’ sketches assessed by external judges.

2) Timing and analogical reasoning

The generation of new design ideas is the process which can take from a few seconds to several days and thus it seems obvious that there is an essential time factor to be taken in consideration when studying design activity. [Tseng et al., 2008] designed an experiment to evaluate the effect of timing of information accessed by designers when trying to solve a problem. Among several findings, it was shown that information that is more obviously similar to the problem impacted idea generation process more than distant information when accessed before the problem-solving task had started. This finding confirms that there visual perception and image use are not only a matter of content (related or distant information) but also a matter of timing; as design cognitive processes definitely are time-related, further studies should integrate the time factor.

3.3 Preliminary investigations on images perception in the design process

Limitations of previous studies: it is based on the hypothesis that what a subject (designer) sees in the image is what the experimenter sees in the image. But, we think that the designers go through an perception/interpretation step which might not be taken into account by the experimenters and thus lead to distorted analyses when the experimenters correlate visual information seen by designers and design outputs. Therefore we proposed to investigate how designers actually perceive visual information, with a focus on the “level of abstraction”. We set up an experiment with four subjects, professional designers in Italian car-design companies. After receiving a design brief, the designers had to browse a selection of magazines from various fields, to retrieve the images they found interested in the context given by the brief and to annotate each selected images with explanations about the reasons of the selection [Mougenot et al., 2008]. Based on the annotations, the images were then broken down into three categories (high, medium and low level of abstraction) by the experimenter, as described in table 3.

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<thead>
<tr>
<th>Abstraction level</th>
<th>Typical content</th>
<th>Examples</th>
</tr>
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<tbody>
<tr>
<td>High</td>
<td>Atmospheres, sensations</td>
<td>Cool. Provocation.</td>
</tr>
<tr>
<td>Medium</td>
<td>Products or sectors names</td>
<td>Architecture. Cars.</td>
</tr>
<tr>
<td>Low</td>
<td>Materials, colors, textures</td>
<td>Colors. Shapes.</td>
</tr>
</tbody>
</table>

It was found out that most selected images were annotated with high level terms (29 images over 70) or low
level terms (26 images over 70), while “medium level” images did not draw much of subjects' attention. It can be assumed that designer either pick images which create an atmosphere or provide sensations (high level) or images which give detailed information about concrete design elements (low level). A question that raises from our findings is related to the earlier-mentioned time factor: we would like to investigate whether the type of images is dependent on the time in the design process and our hypothesis is that high-level images might be more useful at the beginning of the ideation process and low-level images when the ideation is more advanced. These preliminary findings showed that designers retrieve different kinds of images when browsing visual information (images with low and high level of abstraction). Further investigation will focus the relationship between the level of abstraction of inspirational images and the level of creativity of design outputs.

4. Towards qualitative investigations on implicit design process

Former design studies brought information about design activity and its cognitive correlate. When dealing with similar cognitive operations (e.g. visual perception), findings in cognitive science can bring new insights into design science. In this section, we report a selection of relevant investigations in cognitive science.

4.1 Trend in cognitive studies: investigating creativity in professional practices

As explained by [Fink et al., 2009], most of creative thinking tasks which are studied in cognitive and neuroscientific research are basic types of tasks and most of the experimental studies are based on tasks consisting of verbal stimuli. Thus, these experiments can only end up with findings on basic aspects of creative thinking. From a neuroscience point of view, research in the field of creativity is challenged by the studies of real-life complex creativity tasks. Besides, most of the studies in this field of research investigated brain activity patterns in samples of university students or in samples of the normal population. There are very few studies in neuroscience which involve specific samples who have a creative practice, such are designers or musicians. Noteworthy exceptions are the studies who investigated brain activity in samples of scientists [Bhattacharya & Petsche, 2002], artists [Chávez-Eakle et al., 2007] and dancers [Fink et al., 2009]. In the trend of studying creative professional practices, we are convinced that cognitive and neuroscientific investigations on designers' activity would bring useful advances to cognition knowledge and to creativity studies.

4.2 Visual perception: relevant neurosciences findings

Design activity involve cognitive operations as creativity, problem-solving, memory, attention, perception so it is expected that the exploration of cognitive science and neuroscience studies through the prism of design studies brings in-depth knowledge of design processes and activities. Most investigations by cognitive scientists and neuroscientists are held outside the specific context of design activity. Since it has been shown by design studies that the use of images has a major role within the design process; it is therefore highly relevant to review investigations about the perception of visual information [Watanabe & Shimojo, 2005] [Ariga et al., 2007]. Other recent studies explored brain activity in visual mental imagery and visual perception, with traditional approaches in neurosciences: functional magnetic resonance imaging (fMRI) as [Ganis et al., 2004] or event-related brain potential (ERP) as [Qiu et al., 2007]. Other cognitive operations are involved in the design process, such as attention, visual attention, color perception...

More specifically, we propose to investigate the perception of images and the visual imagery process, with a focus on the type of visual content: animate/inanimate things and level of abstraction. This core idea is based on recent findings in neurosciences which depicts that the human brain discriminates images based on their content and processes them in various areas. Thus, the organization of the human visual system is based on high-order
objects recognition processes. Face recognition is widely known to be processed by a specific area of the brain (in a part of temporal lobe called Fusiform Gyrus) but this type of processing not only concerns pictures of faces. In fact, several Functional Magnetic Resonance Imaging (fMRI) studies reported by [Mahon et al., 2007, 2009] have shown that the brain discriminates living things vs. non-living things and manipulable objects (tools and utensils) vs. large non-manipulable objects (scenes). In fact, images of manipulable objects are processed by Fusiform Gyrus while images of non-manipulable objects are processed by Parahippocampal Gyrus. This differentiation in brain processing is particularly relevant in the context of design where designers handle and use all kinds of images, not only images of precedents, as studied by most design investigations so far, but also images of highly-contextualized objects as scenes or landscapes [Mougenot et al., 2008].

4.3 Future investigations on visual perception in design activity

So far, most investigations on design creativity have focused the visualization and use by designers of images of manipulable objects, being intra-domain or inter-domain precedents. Extending former studies in design science and based on findings on brain processing, our hypothesis is that design creativity is influenced by the type of images visualized by designers: manipulable vs. non-manipulable objects. A sub-hypothesis is that the visualization of highly-contextualized images (scenes, pictures with a high level of abstraction) would lead to a higher level of creativity. To test this hypothesis, our future experiment will rely on methods from both design science (protocol analysis, interviews, sketches assessment) and cognitive science (measuring body and brain activity), as explained in table 4. We propose to investigate the implicit processes in designing activities by using eye-tracking, motion capture, digital pen and tablet, and brain imaging devices, in combination with careful observations and interviews on the explicit process.

Table 4 : Characteristics of investigations on explicit and implicit processes of design activity

<table>
<thead>
<tr>
<th>Part of design activity</th>
<th>Typical observations</th>
<th>Methods / tools</th>
<th>Experimenters</th>
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<tbody>
<tr>
<td>Explicit process</td>
<td>Browsing images</td>
<td>Observations, interviews, sketches analyses</td>
<td>Design scientists mainly</td>
</tr>
<tr>
<td></td>
<td>Sketching creative outputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implicit process</td>
<td>Visual perception</td>
<td>Eyes-tracking, motion-capture, brain imaging, fMRI, ERP</td>
<td>Cognitive scientists and neuroscientists mainly</td>
</tr>
<tr>
<td></td>
<td>Analogical reasoning</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emotional arousal</td>
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The experiment variable will be the content of images: sets of images with various types of content (living objects, manipulable objects, scenes) will be used to identify possible effects onto creativity. While the subjects are engaging in design tasks, actual strokes in sketches and eye movements will be analyzed with manipulations of visual materials of different kinds. During the experiment, body and eye movements will be recorded and related to the time when subjects experience inspirations, to find implicit signatures of creativity.

5. Conclusion

So far, most design studies, included our work, investigated the explicit design process by observing external pieces of evidence of designers’ work: for instance, to evaluate design creativity, usually visible external representations (sketches) are collected and assessed by judges. From the visualization of inspirational images to the production of sketches, inputs and outputs of the design informational process usually are tangible components, easily captured and assessed. But design process involves many highly complex cognitive operations; we proposed then to investigate further these cognitive operations and to study in-depth components of designers’ creativity such as visual attention and visual perception from the points of view of both design scientist and cognitive scientist. More specifically, we propose that further studies should investigate the effect of the content of images visualized by designers onto design creativity, including not only images of design
precedents but also images of scenes. Bridging design studies and cognitive science is highly relevant when aiming at a comprehensive knowledge of design process; therefore future design investigations jointly carried out by both design and cognition scientists are expected to bring knowledge on implicit process of design activity and specifically on the link between visual perception and creativity.

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