Visualization Method of Design Cognitive Process Based on Semantic Circle

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Abstract. The visualization of design cognitive process can help to understand the cognitive style of designers and analyze the causes of design ideas quality. This study aims at understanding the cognitive styles from the perspective of the semantic distance between memory-retrieved precedents and design goal. A protocol study was conducted with 26 master students majoring in industrial design. After obtaining a set of design precedents based on the design goal, the semantic distance between design precedents and design goals was analyzed through semantic network. To describe relevance of the semantic distance to cognitive processes, this study devised a new way called ‘semantic circle diagram.’ It supports intuitive interpretations of design cognitive process and output results, while visualizing the elements of different design stages. Based on semantic circle diagram, the cognitive styles of each participant were derived, and the design ideas quality generated by different cognitive styles was discussed. The results of this study provide an individualized reference for design cognitive research and design thinking education.

Keywords. cognitive styles, design precedents, semantic circle diagram, design process, design thinking education

1. Introduction

Design thinking shows the difference in individual design cognitive style among different designers. Design cognitive style is described as a typical or habitual pattern of how a person solves problems, thinks, perceives, and remembers [1]. As many studies have categorized and summarized the cognitive styles of designers about the usage of design method, researchers analyze design process and logic in a variety of forms and ways. Existing studies tend to identify design styles by describing multiple minds at different stages of design process. However, poor correlation between analysis and conclusion, inadequate visualization of cognitive styles, and lack of practical application value remains to be addressed. In most cases, design process is too complicated to analyze and to find meaningful insights even after they are encoded. As a result, a description approach that is capable of summarizing and showing the significant patterns of cognitive processes is necessary. However, it is hard to find a method which satisfies all of these needs.

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Memory retrieval is vital in creative design tasks, according to cognitive psychology study. The empirical information acquired from memory retrieval is called precedent. The design precedents promote design activities by providing a reference that help to deal with design problems. In this regard, this study employed a new way to visualize the cognitive process which supports analysis and interpretation of the role of design precedents. We brought the perspective of semantic network to analyze the correlation of design precedents to design goal. We aimed at representing the comprehensive structure of a cognitive process while describing the elements of the different design stages. Is it possible to conduct a study from the differences of memory retrieval? Is it possible to group these differences into a limited number of cognitive styles with different characteristics? Is there a relation between distinct cognitive styles and design innovation ability? In order to research these questions, a new visual analytic diagramming method is proposed. It mainly evaluates the design process and displays the cognitive style differences by analyzing design precedents. Designers can use the diagramming method to simply deconstruct their own design process and get personalized development suggestions.

2. Visualization of Design Cognitive Process

2.1. Design Precedents for Memory Retrieval in Cognitive Process

Precedents is one of the most important elements in developing ideas. Design, according to Oxman, is a type of generalization and classification that transforms empirical knowledge into design knowledge [2]. In memory retrieval, there is some direct experience as well as structured knowledge. Designers use these precedents to comprehend and assess solutions in addition to design problem identification [3-5]. Novice designers, according to numerous research findings, require precedents to assist them in gathering information, iterating through all stages of the design process, and producing different solutions [6-9]. Throughout the process, precedents aid designers in developing their unique design approach. Meanwhile, not only in the design process, but also in the development of design expertise, precedents are actively involved [10]. As such, depending on the designers' level of expertise, the degree of reliance on prior knowledge and experience may vary.

The utilization of prior knowledge is related to design outcomes as well. In the design process of analogical reasoning, researchers usually regard the link between memory-retrieved precedents and design goals to be a significant factor for innovative ideas generation [11]. Many studies have tested the connection between precedents and goals. It is found that a design precedent with low correlation to the design goal may lead to higher innovation [12][13]. A design precedent with strong correlation to the design goal may result in design fixation [14][15]. In this study, we hypothesized that there are significant individual differences in the usage frequency of precedents and the degree of correlation between the precedents to design goals. The designer's cognitive style may be reflected from it.

2.2. Visualization Elements of Cognitive Process

In design problem solving, there are approaches that use precedents to analyze problems [16], analogical reasoning [17], and reorganize various information [18]. These cognitive

stages that apply precedents influenced the design progress. Design elements extracted from different stages of cognition can be used to analyze the design process and study cognitive activities.

Some studies have divided the overall design process into several design elements. Oxman proposed a model to represent chunks of knowledge of designs. The model contains three elements: the issues of a design problem, a solution concept, and a related form description [9]. Problem structure, empirical search, sensing, idealization, and evaluation are the five elements of divergent thinking process proposed by Khandwalla [19]. In addition, there are a lot of information related to memory retrieval, cognitive operations, and evaluation iterations included in a complete design process. Researchers have focused on abstracting different kinds of information from a design process in order to extract essential design elements. In this study, we selected memory-retrieved precedents, analytical reasoning fragments, initial ideas, and final ideas as the design elements. After documented the design process through video and text [20][21], we analyzed and visualized these design elements in a cognitive process diagram.

2.3. Relations Among Visualization Elements of Cognitive Process

The difference between various design methods is the variety of combinations between design elements. There is usually a progressive and parallel relation between the elements. This constitutes the difference between ‘depth-first’ method and ‘breadth-first’ method [22]. In most cases, designers prioritize solutions in early stages of design. Some designers spend more time identifying potential problems before setting a solvable direction [23]. Some designers acquire a lot of information during the design process, evaluate as many alternative ideas as possible. Experienced designers prefer to conduct a program evaluation to see whether the basic concept is worth moving forward into a deepening idea [24]. When problems in an idea are discovered, most designers prefer to modify or iterate it rather than discarding it [25]. These studies highlighted that designers have different design preferences in the creative process.

Linking these design preferences and cognitive process, we proposed a question: How are the elements at different stages of design process related to each other? Visualizing the relations between design elements can help to understand the creative design process. In this study, the cognitive process diagram mainly shows the following relations: progressive and parallel relations between precedents, relations between precedents and ideas, relations between the ideas, iterative relations of final idea.

2.4. Existing Visualization Methods for Cognitive Process

Some researchers study the visualization of design cognitive process from different perspectives. A linkography method represents a design process in terms of a combination of successive ‘design moves’, and links between them [26]. The cognitive map analyzes the way each person uses precedents and the impact of precedents on design outcomes while reducing the time order of design process [6]. Most visualization studies of cognitive process rely on manual processing of information to ensure objective segmentation and coding of experimental information.

In order to provide valuable insights and an intuitive way of explaining cognitive processes, we focused on representing the design process by visualizing the multifaceted relations among design elements. We concerned with effectively summarizing and explaining the generative patterns of design precedents. [27]. The possibility of using

semantic network methods to determine the semantic distance between precedents and goal was discussed in this study. Semantic network theory constructs a model of representational and factual information of human memory. Quillian proposed that different words can be linked through the correlation elements between semantics to form semantic networks with themes, forming the theory of free word association [28] [29] [30].

This study adopted design goal as a semantic topic. It also represented the correlation between design precedents and goal in terms of the distances in semantic network. The distance between semantic topic and design precedents was divided into three levels, corresponding to the three layers of the semantic circle diagram. Through using this method and combining with other visual elements, we were able to suggest a novel way to make the cognitive processes apparent.

3. Experiment

3.1. Subjects

26 postgraduate students (13 male, 13 female) majored in industrial design participated in this experiment. Their ages ranged from 23 to 26.

3.2. Experimental Procedure

These subjects were required to use the think-aloud method throughout the experiment. The language information recorded in videos would be converted into text form in later analysis. A 10-minute pre-experiment session took place before the 35-minute formal experiment. The design theme of pre-experiment was ‘cups on the plane’. The purpose of pre-experiment was to ensure subjects thoroughly adjust to the think-aloud method, as well as to forecast and avoid potential problems in the formal experiment.

Formal design theme was ‘tables and chairs in the library’. This design goal took the design experience of different students into consideration. Electronic devices were not permitted to use throughout the experiment. After obtaining the set of memory-retrieved precedents based on the design goal, we performed coding analysis for design precedents which is to determine the semantic distance between the design precedent and the design goal. To ensure the accuracy of the coding, we invited five postgraduate students majored in industrial design to extract semantic keywords from each set of precedents. They set up a semantic link network centered around the design theme ‘tables and chairs in the library’. The structure of semantic network refers to many studies on semantic conceptual model [31][32]. In this study, the distances between semantic keywords and topic words were classified as near, medium and far.

4. Analysis Process of Semantic Circle Diagram Method

4.1. Data Processing and Analysis

According to the above study, the following elements were proposed for data processing and coding.

- Near, medium, and far memory-retrieved precedents (p1, p2, p3): In Step 1, we converted the oral information into texts and extracted the memory-retrieved precedents (e.g., “Tables and chairs are not like those in fast food restaurants, I remember my teacher said that he went to KFC...”). In Step 2, we extracted semantic keywords from memory-retrieved precedents (e.g., “Hard chair in KFC”). In Step 3, based on semantic link network, we judged the semantic distance between each set of design precedents and design goal (e.g., near). Finally, we coded the near, medium and far precedents as p1, p2, p3. The near precedents correspond to the first level of semantic circle, and the far precedents correspond to the third level of semantic circle.
- Analyze (A): The flow among precedents and the impetus of precedents on idea generation were unified into analytic reasoning fragments. We inserted punctuation marks into the experimental text to distinguish between progressive and parallel relations in reasoning.
- Initial idea (II) and final idea (FI): In the idea generation, subjects had a lot of hand-drawn movements and explanation of the ideas which may lag after the actual thinking process. We timed the creation of the idea according to hand-drawn gestures in the video. At the end of experiment, the subjects were asked to calibrate the final idea. We marked the other ideas that were formed before the final ideas as initial ideas.

4.2. Visualizing Design Process

The semantic circle diagram visualizes the 35-minute design process into a closed and clockwise circle with the design goal as central focus. The design precedents appeared relatively short compared to the overall design process. It was easier to mark the point at which a precedent first appeared than to show its duration line on the diagram. The semantic distances between precedents and goal were evaluated using semantic network theory to build a three-level circle.

In the semantic circle diagram, arrows and ovals represented progressive and parallel linkages of the analytical reasoning. The first and final ideas were marked in the outer circle, so that the order and total number of ideas were clearly visible. The diagram contained the chronological representation and the direction of analytical reasoning. It was possible to indicate the logic of progression between design precedents and ideas. The subjects’ preference for using precedents and the contribution path from initial idea to final idea were displayed. An example of semantic circle diagram is shown in Figure 1. It effectively conveys specific information about the cognitive process and makes it easier to distinguish between different types of activities.

Figure 1. An example of semantic circle diagram.

5. Design Style and Innovation Capability on Semantic Circle Diagram

5.1. Design Cognitive Styles on Semantic Circle Diagram

This study analyzed 26 subjects’ cognitive process using semantic circle diagram. Eight cognitive types were identified, which are shown in Table 1. The typical diagrams of the eight cognitive styles are shown in Figure 2.

Table 1. Distribution of design cognitive styles

Cognitive style	Subject
p1+p2+p3+	1
p1+p2+p3-	2, 11, 12, 6, 13, 17, 22
p1+p2-p3+	23
p1-p2+p3+	4, 8, 14, 20, 26
p1+p2-p3-	3, 5, 7, 15, 16
p1-p2+p3-	10, 25
p1-p2-p3+	9, 24
p1-p2-p3-	18, 19, 21

- a. p1+p2+p3+Equilibrator: Precedents are evenly distributed among the three levels of circles. The precedents in the second level led to more design ideas. The subject could make full use of the precedents in the analytical reasoning process to promote idea generation. During the whole design process, several ideas were generated, and the iteration speed was relatively fast.
- b. p1+p2+p3-Prudent man: There are fewer precedents and ideas. Before coming up with ideas, the subject tended to do a thorough preliminary analysis and think outside the framework of the design goal to ensure that he/she did not deviate from the design requirements.

- c. p1+p2-p3+Interrupter: The subject had almost no precedent on the second level of semantic circle, while there is a leap in thinking during the design process and richer thinking divergence in the early stage. He/She retrieved multiple similar precedents at a single point to locate design problems. The design idea was reviewed and reinforced with some precedents with weak relevance to the design goal in the final stage.
- d. p1-p2+p3+Explorer: The precedents are less in the first level of semantic circle and more concentrated in the outer circle. The subject might desire to use far precedents to identify new design challenges and improve innovation ability. The generation of design ideas is evenly distributed, which indicated that the subject could control the design direction well.
- e. p1+p2-p3-Focuser: The precedents are basically focused on the central region of the semantic circle. There are many pieces of parallel relations in the design. In the middle of the design process, the subject seemed to be blocked and could not come up with a satisfactory solution quickly. Near precedents tend to trigger design fixation.
- f. p1-p2+p3-Selector: The number of precedents in the design process is quite minimal. The subject was inclined to retrieve the second level of precedents and had a strong grasp of design approach.
- g. p1-p2-p3+Adventurer: There are few precedents but more ideas, fast iteration between initial and final ideas. The subject was inclined to retrieve less relevant precedents to stimulate idea generation.
- h. p1-p2-p3- Pessimist: The numbers of precedents and ideas are quite small. The subject selectively retrieved memory around the design goal to aid in idea generation.

5.2. Cognitive Styles and Innovation

Three experts with at least three-year experience in the furniture design assessed the innovation of the 152 ideas. The evaluation was set to three grades, e.g., poor (103), medium (38), and good (11). Table 2 shows the distribution of the subjects' precedents in the three levels of semantic circle and the innovation grades of their ideas.

The average of design precedents was calculated for each level of the semantic circle. In this study, the subject who produced the precedents more than the average was considered to have an apparent propensity to use the precedents (p1+, p2+, p3+), and who generated medium and good ideas more than the average was considered to have high creativity (C+).

It is clear from the Table 2 that the generation of highly innovative ideas need far and medium precedents (p2 and p3) to stimulate. The result consistent with the previous studies that precedents with far distance from the design goal can promote higher innovation [12][13].

Table 2. Precedents distribution and innovation comparison

Subject	Precedents Distribution			Number of ideas			Cognitive style-Creativity
	P1	P2	P3	Poor	medium	good	
Avg.	11.7	4.7	2	4	1.5	0.4	$P(p1\pm p2\pm p3\pm)\pm C\pm$
01	15	10	4	7	2	1	$P(p1+p2+p3+)+C+$
02	20	10	0	3	3	0	$P(p1+p2+p3-)+C+$
03	12	3	0	3	2	0	$P(p1+p2-p3-)-C+$
04	6	5	3	10	3	0	$P(p1-p2+p3+)+C+$
05	10	1	0	5	0	0	$P(p1+p2-p3-)-C-$
06	15	6	0	3	0	0	$P(p1+p2+p3-)+C-$
07	21	2	1	11	0	0	$P(p1+p2-p3-)-C-$
08	9	6	4	0	4	0	$P(p1-p2+p3+)+C+$
09	9	2	3	3	1	1	$P(p1-p2-p3+)-C+$
10	5	7	0	4	2	2	$P(p1-p2+p3-)-C+$
11	10	5	2	4	8	0	$P(p1+p2+p3-)+C+$
12	14	5	0	4	2	1	$P(p1+p2+p3-)+C+$
13	14	11	2	7	1	0	$P(p1+p2+p3-)+C-$
14	5	6	8	5	1	1	$P(p1-p2+p3+)+C+$
15	14	1	0	4	1	0	$P(p1+p2-p3-)-C-$
16	20	2	0	5	1	0	$P(p1+p2-p3-)-C-$
17	15	11	1	2	0	0	$P(p1+p2+p3-)+C-$
18	4	3	0	2	0	0	$P(p1-p2-p3-)-C-$
19	9	0	0	2	1	0	$P(p1-p2-p3-)-C-$
20	3	9	14	6	2	0	$P(p1-p2+p3+)+C+$
21	9	3	1	5	0	0	$P(p1-p2-p3-)-C-$
22	19	7	0	2	0	0	$P(p1+p2+p3-)+C-$
23	16	1	6	0	1	0	$P(p1+p2-p3+)+C-$
24	4	1	4	0	3	4	$P(p1-p2-p3+)-C+$
25	7	8	0	4	0	1	$P(p1-p2+p3-)-C+$
26	9	5	3	1	0	0	$P(p1-p2+p3+)+C-$

6. Discussion

This study focused on the cognitive styles from the perspective of the semantic distance between memory-retrieved precedents and design goal. Twenty-six industrial design postgraduate students took part in the design experiment and explained their thinking process. Memory-retrieved precedents, analytical reasoning fragments, initial ideas, and final ideas were all coded in detail for the correlation analysis between design elements in cognitive process.

A visualization method of semantic circle diagram was proposed to describe the relations among the design elements. We focused on the distribution of precedents through semantic network analysis. The semantic circle diagram, in comparison to other

approaches for visualizing cognitive process, gave a visual interpretation of the design cognitive process and output ideas. It supported the visualization of thinking process of each designer. By analyzing each subject's semantic circle diagram, eight cognitive styles were identified, e.g., Equilibrator, Prudent man, Interrupter, Explorer, Focuser, Selector, Adventurer, and Pessimist. Finally, this study provided a statistical discussion of the correlation between cognitive styles and ideas' innovation.

In conclusion, the visualization method is helpful to the analysis of design process and the understanding of design cognitive style. Designers can use the semantic circle diagram to better understand their own design cognitive style and improve their innovation ability. In the future study, we will define the characteristics of each cognitive style and corresponding developmental recommendations for designers. It will play a more rational and scientific role in future design education. Furthermore, design process analysis relies on a lot of manual labor, making it difficult to establish accessible, stable, and accurate standards for the analysis process. Advanced data mining tools will be better able to assist the task of cognitive process visualization.

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