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A COGNITIVE APPROACH TO THE ANALYSIS OF DESIGN PROCESSES

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ABSTRACT

The scientific analysis of design is indispensable in order to establish a rich and useful design theory. Accomplishing this, we propose a practical method to investigate design named *design experiment* and methods to analyze its results. Since the design experiment is performed mainly with the protocol analysis method, We start from discussing the experimental method in comparison to psychological experiments. Furthermore we introduce a new method using a CAD-like system which can record drawing processes precisely. We analyze the protocol data in two ways. One is the analysis by extraction of knowledge. Using this we can clarify how knowledge is used and what knowledge is needed in design processes. The other is based on the cognitive approach. Protocol data is transformed into the semantic network of concepts which is used as the network in the connectionist paradigm. We can identify what the designer pays attention to and how it is changing in design processes by regarding the activations of nodes as the intensity of the designer's attention.

1. INTRODUCTION

The concept of intelligent CAD systems has drawn attentions of researchers in both the engineering field and the AI field, and various studies have been reported as its realization. Recent development of computer technique and artificial intelligence makes it possible to propose and implement such intelligent CAD systems. However, these systems seem to be built as merely applications of expert systems' technology. Since design is one of the most intelligent human activities, it is needed to make efforts in investigation of design itself and we believe that better development of intelligent CAD systems would be done only on the basis of such investigation. This means that theoretical research to design, i.e., design theory is needed.

In this paper we describe an experimental method to analyze design and some of the results.. In Chapter 2, we show the background of our research and present the method we use. We call our method a *design experiment* in which designers are asked to perform design and the whole session is recorded on video tape. We discuss the experimental method in comparison to psychological experiments. We did two types of design experiment which were different in collecting information. In the first one we use the conventional protocol analysis and in the second one we adopt the new method which we developed to collect graphical information more precisely. We show the results and the analysis of the first experiment in Chapter 3 and the second experiment in Chapter 4. Chapter 5 concludes the paper.

2. DESIGN EXPERIMENT

2.1. Research of Design Processes

Design is a complicated process of human thought and it is dependent both on internal environments such as human ability of problem solving or experience, and on external environments, such as requirements of products. The designer modifies and adds details to the design object by using her/his own design expertise (i.e. her/his experience of past designs, her/his engineering knowledge and know-how, established design procedures). During the initial stage of the design the descriptions of design objects are poor and incomplete, because they consist of only specifications of the design and the specifications themselves may be uncertain, incomplete, and contradictory. As the design proceeds, uncertainty and incompleteness are progressively removed and the problem converges to a solution.

There proposed theories to describe design generally and most of them can be classified as design methodologies (for example see (Hubka, 1982), (Roth, 1982)). But they are not completely successful as a design theory because it is almost impossible to adapt them to different domains. One reason of this is that design is too various and diverse and that it is not an easy task to discuss design generally. There is another reason, i.e., traditional design methodologies are based on the researcher's experiences and textbook knowledge of the domain and their purpose is to present how to design and how to design good products. Therefore they lack generality and flexibility beyond domains.

Our aim is to establish a logical framework to represent design processes more generally and formally. It is clear that this cannot be achieved without scientifically extracting information about design processes. But it is difficult to perform this by simple observation of design activities, because they are diverse, personal, and complex activities. One useful method to perform observation is the experiment. Various kinds of scientific knowledge have been obtained by experiments. We have suggested an experimental approach to investigate design and called it a *design experiment* (Yoshikawa *et al.* 1981), (Yoshikawa 1983). In our experimental way we can prepare desired conditions and put everything under control to reduce the difficulty of the observation and subjectiveness.

Using results obtained by experiments, we try to get a *cognitive* model or a *cognitive* design theory of design processes. It is expected to explain designer' behavior and describe design processes. Using these models, we are trying to establish logical formalization of design processes (Takeda et al, 1990). This is expected to be a *computational* theory (Dixon, 1987), (Kalay, 1987). In this paper, we focus on extracting information of design processes in an experimental way and analyzing the results in a cognitive way (see Figure 1).

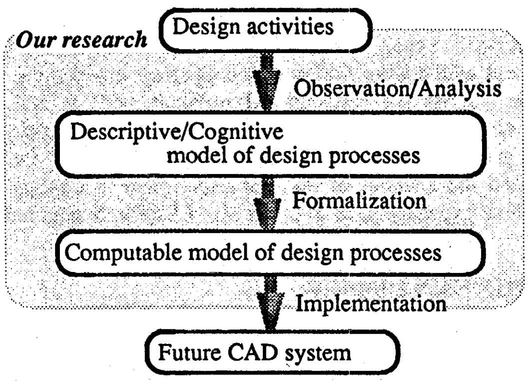

Figure 1: Framework of Research of Design Processes

There are some works based on the experimental method: e.g., Ullman *et al.* (1987, 1988). Waldron *et al.* (1987, 1988), and Goel and Pirolli (1989). Perlman (1988) reviewed and criticized Waldron's work, Ullman's, and so on. He compared the methods of gathering information and concluded that more controlled experimental methodology might provide more insights into the design process. Therefore we start from discussing how the experiments should be performed and how and what information should be obtained.

2.2. Method of Design Experiment

In this section, we discuss our experimental method to examine its validness for analyzing design processes. We discuss it from two viewpoints, i.e., a viewpoint of design and one of psychological experiment.

Design experiments collect information of design processes according to the *protocol analysis* method from the viewpoint of psychological experiment (Ericsson and Simon, 1980). The designers are required to solve a design task by *thinking aloud*, i.e, speaking what they think during they solve it. While solving it, we collect what they say and their actions by video recorder and their drawings by making copies once in every several minutes.

There is a useful discussion how we can trust verbal protocol as information about human thinking process (Ericsson and Simon, 1980). Ericsson and Simon discussed effects of probes and instructions to verbalize, completeness of verbal reports, and so on. Based on this discussion, we can identify following three conditions to perform experiments in order to obtain trustful information.

(P-1) Subjects are not allowed to know the aim of the experiment.

(P-2) The task should not be familiar to subjects.

(P-3) The environment should be provided in which subjects can verbalize a lot.

Dixon identified the following parameters that influence design processes from the viewpoint of design.

(D-1) the person or persons (the designer or designers)

(D-2) the problem (the task)

(D-3) the organizational environment

(D-4) the design environment

(D-5) time

We can discuss how a design process in the design experiment is similar to actual design processes by checking these points.

- The designers

We asked engineers and students as subjects. The former were engineers working in an industrial company for 5-10 years, and the latter are graduate students in precision machinery engineering department. We can see the effect of the parameter (D-1) by comparing engineers and students. We were careful not to let the subjects know what part of their verbalization would be analyzed and asked them to do what they do in usual in order to keep the condition (P-1). Nevertheless, they sometimes tried to guess our intention in experiments.

- The task

The design task must satisfy the following conditions.

(1) The function of the machine must be specified clearly.

(2) The machine must be realizable.

(3) The mechanism of the machine is not known to the designers.

(4) The design must be accomplished only with general knowledge about mechanical engineering.

(5) The design process must be finished in several hours (i.e., in a day).

We provided the first two conditions, because designers should accomplish their tasks successfully. Conditions (3) and (4) were needed to avoid routine or regular design processes. The task familiar to the designers violates the condition (P-2). However, it caused the parameter (D-2) different from the one in actual design. Thus, it is a difficult problem to decide a task keeping these two conditions. In our experiments, we chose the tasks to keep the former condition. We must avoid long suspensions, because designers may think about the problem during the break and we cannot know the thought. This is one reason for (5), and the other reason is that too long protocol is difficult to analyze.

- The design environment

We require more than two designers to solve a single task together to keep the condition (P-3), while protocol analysis is usually performed by a single subject. Because usually tasks used in psychological experiments are not complicated, it is not so difficult for subjects to *think aloud*. Contrarily design tasks are so complicated and so difficult to solve that it is hard to think and speak simultaneously. Nevertheless if we force designers to think aloud, the design process would be spoiled and it would be different from what is expected to be done. Since designers are allowed to talk with each other in our method, their thought is expected to appear in their conversation to understand with each other in natural. That is the reason why we chose the experiments by two designers. Furthermore we used a drawing system which will be shown in Chapter 4. Although it makes designers' behavior different depending on the experience of CAD systems, we can obtain more precise information about drawings and analyze the protocol data more precisely by referring to the precise data of the drawings.

We discussed the detail of our method in which careful preparations were provided to keep the conditions from the viewpoint of psychological environment and to make the parameters from the viewpoint of design. In following chapters, we show two types of design experiments performed under these preparations. They differ in the method to gather information and the method to analyze design processes. We call them Experiment I and Experiment II respectively. In the first one, we gather information in the way described above and analyze the contents of the protocol data by knowledge classification. In the second one, we use a CAD-like system and analyze the protocol data by the network of concepts.

3. EXPERIMENT I

3.1. Preparation and Result

In Experiment I we conducted three experiments with six designers. Four of them are engineers working in an industrial company and the rest are graduate students in a university (see Table 1). First two experiments (No. 1 and No. 2) were performed by two pairs of two engineers. Experiment No. 3 was performed by two students as a comparison experiment in order to compare the difference between engineers and students. The task is to design a scale with specifications described in Figure 2. The results are shown in Table 1.

Table 1: The Results of Experiment I

Experiment	Designers	Time	Sentences	Drawings
No. 1	two engineers	5:00	about 360	50
No. 2	two engineers	5:20	about 320	32
No. 3	two students	3:35	about 270	42

Design a prototype of a scale which satisfies following conditions;

(1) The sizes are 300 mm height, 250 mm width, and 50 mm thickness.
(2) You can specify where to put feet.
(3) Never use electric parts.
(4) Don't concern the strength of parts seriously.
(5) The maximum of the weight is 100 kg.
(6) When 100 kg weight is loaded, the upper plate goes down by 5 mm.
(7) A draft is required as a final output.
(8) You can refer catalogs about gear and so on.

Figure 2: The Task of Experiment I

3.2. Analysis

3.2.1 Method

The analysis for this protocol data carried out to extract and classify design knowledge. There are different discussions about what is knowledge and how it can be define, but we provide a simple definition in this research. We assume that knowledge is appeared as a piece of verbal protocol which represents a content of the designer's long memory or outer sources used to proceed the design. For example, the designers said "What type of spring can be used instead of coil spring?" and "Leaf spring. But leaf spring is not good in accuracy.", then we can obtain "Coil spring is used as spring", "Leaf spring is used as spring" and "Leaf spring is not good in accuracy" as knowledge. We could find 134 pieces of knowledge in the two experiments.

Then we classify these pieces of knowledge as relation from a concepts to the other concept, Since knowledge appears when one thing reminds the designer of something different. In order to do this, we first classify concepts used in knowledge into seven categories, i.e, *entity (E), function (F), attribute (A), topological relation between entities (T), connection method between entities (C)* and *manufacturing method of entities (M)*. First three concepts are descriptions about objects. We use them in the same meaning as defined in General Design Theory (Yoshikawa, 1981). Next two concepts are descriptions about relationships among objects. *Topological relation* is a description how the parts are related, for example, followings are classified in this category; "The two gears are engaged together," and "The spring is fixed vertically on the plate." *Connection method between entities* is a description how the parts are connected to each other. Typical examples include "The parts are welded to each other," and "The part is hung on the hook of the other." *Manufacturing method of entities* is a description about how to manufacture. This includes "Automated assembly," and "Cutting out and setting upright."

Thus we got eight categories, i.e., Function→Entity (FE Knowledge), Entity→Function (EF Knowledge), Attribute→Entity (AE Knowledge), Entity→Attribute (EA Knowledge), Attribute→Attribute (AA Knowledge), Topology→Connection (TC Knowledge), Entity→Manufacturing (EM Knowledge), and Manufacturing→Attribute (MA Knowledge)

For example, the first type of knowledge is used when a concept about an entity is recalled from a concept about a function, including such as "Leaf spring is not good in accuracy". The example of EA knowledge is "The diameter of the pulley is 10mm at least", TC knowledge "We can hung the spring on the steel panel by cutting out a part of it and setting it upright.", and so on. There are only eight types listed here, and Figure 3 shows these knowledge categories as relations among the six types of concepts. In the designer's mind, it seems that knowledge on each object or each manufacturing method is gathered and stored as a chunk of concepts as in Figure 3. When the designer uses knowledge, it is transformed from a chunk to a suitable form to be used, i.e., a relation of concepts.

Table 2: The Relationship between Knowledge and Subprocesses

Subprocesses	Knowledge Types								Total
	FE	EF	AE	EA	AA	TC	EM	MA	
Awareness of Problem		5		7					12
Suggestion	22	1	1	15	1	24	1	5	81
Development		1			3		2	2	8
Evaluation		1		16			6	10	33
Total	22	8	1	38	4	24	9	17	134

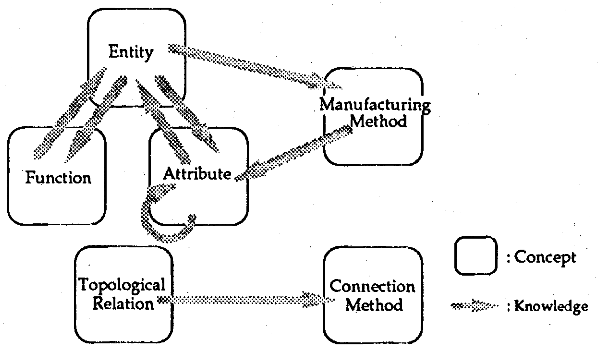

Figure 3: Knowledge as Relations among Concepts

3.2.2 Analysis about Knowledge Utilization in a Design Cycle

Using these types of knowledge, we analyze design processes in two ways. First, we discuss how knowledge is used when the designer solves a problem. We proposed the *design cycle* as a primitive process of design processes shown in Figure 4 (Takeda *et al.*, 1990). It is a cognitive model of design processes and it consists of five subprocesses, i.e., the *awareness-of-problem* subprocess, the *suggestion* subprocess, the *development* subprocess, the *evaluation* subprocess, and the *conclusion* subprocess. Each sentence in protocol data is regarded to represent one of these subprocesses (of course, there are sentences which cannot be classified in any subprocesses). A single design cycle solves a problem and sometimes it causes new problems which are left to be solved by other design cycles. Therefore a design process is represented as a set of design cycles which are connected with each other.

We divide knowledge into five groups according to in which subprocess knowledge is used.[1] Table 2 shows the relationship between knowledge types and subprocesses.

We observe how knowledge is used in subprocesses and found that knowledge is used differently according to in which subprocess it appears. In the *awareness-of-problem* subprocess, knowledge is used to add the specifications or to make them clearer. *EF Knowledge* and *EA Knowledge* are used in this subprocess. In the *suggestion* subprocess all types of knowledge are used, but four types are used mainly. *FE Knowledge* and *TC Knowledge* are used to get a new candidate of design, and *EA Knowledge* and *EM Knowledge* are used to add the reason why the candidate is chosen.

In the *development* subprocess *EM Knowledge* and *MA Knowledge* are used to calculate and estimate the dimensions of parts. *AA Knowledge* is used to propagate the influence of changes of attribute values like dimensions.

In the *evaluation* subprocess, *EA Knowledge* and *EM Knowledge* are used to get values or results that the designer wants to evaluate. *MA Knowledge* is used to get attributes needed to evaluate other attributes; i.e., the obtained attributes themselves are not evaluated.[2]

We showed how knowledge is used in design processes. The type and utilization of knowledge is depended on in which part of design cycles it is used. In other words, knowledge is transformed from the chunk shown in Figure 3 into the suitable form which is the relation between concepts.

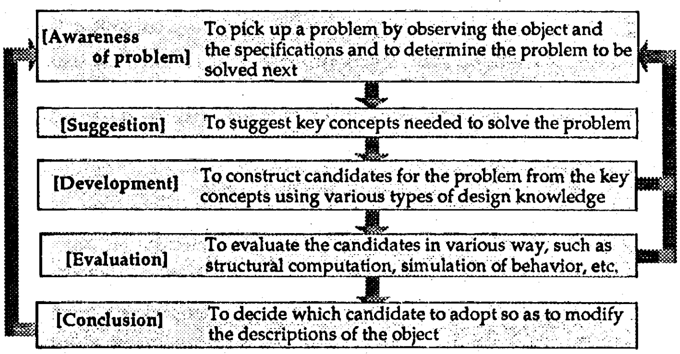

Figure 4: Design Cycle

3.2.3 Analysis about Knowledge Utilization in Design Stages

Secondly, we analyze knowledge utilization in a longer term, i.e., we clarify the relationship between knowledge utilization and the design stages. In traditional design methodology, design processes are divided into some stages and designers perform them one after another, for example, Hubka defined four stages, i.e., clarifying of requirement, conceptualisation, laying out, and detailing (Hubka, 1982). We suppose three design stages, i.e., the conceptual design, the layout design, and the detail design. Generally speaking, the conceptual design is expected to be performed in the early term of design processes, the layout design in the middle term, and the detail design in the later term. We can discuss relationship between knowledge and the design stages by checking when knowledge is used in design processes.

We have classified knowledge into eight types, which can be re-classified into three according to the design stages. Obviously first five types are knowledge about objects themselves, and next one is about relations between objects, and the last two are about manufacturing. It is expected that knowledge about objects should be appeared in the early term of design processes and knowledge about relations and

[1] The *conclusion* subprocess is omitted because it seems to be done more intuitively.

[2] This must be already done in the *development* subprocess, but the designer does not notice what is needed until the *evaluation* subprocesses.

Table 3: Timetable of the Appearance of Knowledge

	Knowledge Types							
	Object					Relation	Manufacturing	
Time	FE	EF	AE	EA	AA	TC	EM	MA
0:00-0:20	5			7				
0:20-0:40				1			1	1
0:40-1:00		3		2		3		1
1:00-1:20	1			2		4		1
1:20-1:40	1			2	2	2	3	3
1:40-2:00								1
2:00-2:20						9		5
2:20-2:40	1					1		
2:40-3:00							1	2
3:00-3:20								
3:20-3:40				1		1		
3:40-4:00								
4:00-4:20								
4:20-4:40				1				
4:40-5:00								

manufacturing in the middle and the later terms of design processes. Table 3 shows a timetable of the appearance of knowledge in Experiment No. 1. It shows that the above expectation is only partly true. Although, generally speaking, knowledge about relations and manufacturing is appeared after knowledge about objects, for most of the cases, it is used simultaneously. In particular, some of knowledge about manufacturing appear at the beginning of the design process. The reason is that the designers first of all estimated the manufacturability of the design objects they intended to use. On the other hand, some of knowledge about objects are found in the later term of design processes in which the designers are drafting. They sometimes checked their design solution in the drafting stage by determining detailed attributes. It means that a simple division of design processes, such as the concept design stage, the layout design stage, and the detail design stage, is not appropriate as a model of design processes. It is needed to develop a more flexible and mixed model of design processes in that design can go backward and forward to other stages as shown in this analysis.

3.3 Discussion

In this chapter, we reported the experiments by the conventional protocol analysis method and analyzed how knowledge appeared and was used in the design process. Analysis of knowledge in design processes can yield various information about what is done during design processes, such as what type of utilization is needed.

Some problems are found. One of them is that although drawing processes and drawn figures apparently play an important role in design, we could not obtain precise information about them. In the next chapter, we discuss another type of the design experiment that was developed to solve these problems.

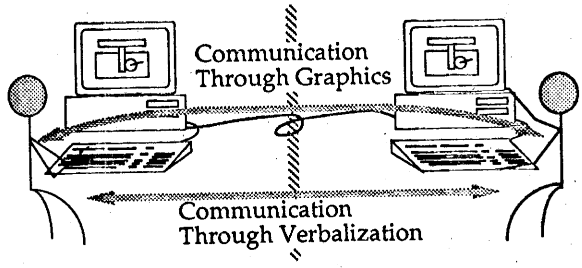

Figure 5: The Experiment with the Drawing System

Design a prototype of a toy that jumps vertically
and satisfies the following specifications.
(1) The sizes are less than 100mm height, 100mm width, and 100mm thickness.
(2) Energy source is a dry cell battery type SUM-3.
(3) It must jump repeatedly after the switch is turned on.
(4) The cycle of jumping is less than 1 minute.
(5) The driving mechanism must be hidden for safety.

Figure 6: The Task for Experiment II-B

Table 4: The Results of Experiment II

	Designers	Time	Sentences	Drawing Operations
A-1	Pair No. 1	2:27	about 1460	247
A-2	Pair No. 2	2:15	about 1190	273
B-1	Pair No. 1	2:27	about 820	334
B-2	Pair No. 2	2:16	about 640	205

4. EXPERIMENT II

4.1. Preparation and Results

To solve the problem mentioned in the previous chapter, we developed a system for design experiments which has primitive functions of a 2D drawing CAD system and also functions to record the users' operations. Because we want to carry out experiments with the same environments as Experiment I except for the use of the system, the two designers must be able to cooperate for a single task on the system. Thus, this system is designed to be used by two designers separately, i.e., each designer operates a personal computer and draws figures on its display. The two personal computers are connected with each other and the system maintains the same figure on the display. Consequently, two way are allowed designers to communicate to each other. All information on figures, including indications of points and areas, is communicated through the system, and the other information is communicated through verbalization (see Figure 5). The data the system records consists of information about all the operations the user made, such as drawing a line, drawing a box, indicating an object, and their timings when the designers execute them. We call this data *drawing protocol*. We combine the verbal protocol data and the drawing protocol data using demonstrative words in the verbal data and the indication operations in the drawing protocol which are corresponding to the words.

In this experiment we prepared two design tasks and carried out two experiments for each task The designers are engineers working in an industrial company for six or seven years. A-1 and B-1 experiments were performed by one pair of designers and A-2 and B-2 experiments by another pair. The task for A-1 and A-2 experiments was to design a rotating mechanism for an electric fan. The task for B-1 and B-2 experiments was to design a jumping toy with specifications described as Figure 6. The results are shown in Table 4.

4.2. Analysis

4.2.2. Purpose and Method

The analysis in this section aims at clarifying what kind of and how concepts are used in the design process. Hasida *et al.* (1987) showed a way to use the semantic network obtained from an article in the newspaper as a network in the connectionist paradigm (Rumelhart *et al.*, 1986), and extracted an abstract of the article (a set of important nodes) with this method. We adopt their method to calculate the degrees of importance of concepts used in the design processes and analyze what designers think in the design process. Hasida *et al.* showed also a calculation method int this approach. They listed two principles of importance of concepts in the context:

(1) If a concept is considered important, the concepts connected to it should accordingly be evaluated high.

(2) The more concepts a concept is connected to, the more important it should be considered.

These two principles are satisfied to adopt the connectionist paradigm that regards the activation of each node as the degree of importance of the node. In the connectionist approach, the network changes its state, as the activation signals propagate along links. The state becomes stable finally after repetition of the propagation, if the convergence is assumed. They adopted an approximation where time is quantized and the signal propagation along links is synchronized. Then the calculation can be simplified as follows: Let all of nodes be numbered from 1 to n. Let $X(t)$ be n vector and the value of $X(t)(i)$ element means the activation of node i at time t. Let C be an n vector and $C(i)$ be the intensity of constant activation to node i. Let A be an $n \times n$ matrix and the value of $A(i,j)$ element is set in proportion to the intensity of the relation between node i and node j (the proportion rate is defined to ensure that $X(t)$ should be converged). Then we can obtain $X(t+1)$ from A, C, and $X(t)$ as follows.

$$X(0) = C \tag{1}$$

$$X(t+1) = AX(t) + C \quad (t=0,1,2,...) \tag{2}$$

Vector $X(t)$ converges to a finite value X as t approaches the infinity. X can be obtained by

$$X = (I-A)^{-1} C \tag{3}$$

where I is a unit matrix. We can obtain X in practise by regarding $X(k)$ as X where $X(k)$ is approximately equal to $X(k-1)$, and it can be calculated by using formula (2) repeatedly. Since the values of most elements in matrix A are 0, this calculation is practical rather than using formula (3) directly.

In our approach, a node is a concept mostly uttered as a noun or a noun phrase in the protocol data. Most of the concepts appeared in the design process are descriptions about objects and instances of objects, and they also include some abstractive concepts such as *clockwise*. A link is a relation between objects which is mostly uttered as a verb. We predefined three kinds of relations, viz. *isa* relation (A is a B), *inst* relation (A is an instance of B), and *has* relation (A has B). Other relations are created when needed. Figures are also transformed into relations in which a node is an object (e.g., a box) or a figure itself and a relation is a *part-to-whole* relation or an *indication* relation which connects a concept in the verbal protocol data with an object in the figure. We obtained 254 nodes and 726 relations from experiment B-1, and 301 nodes and 1109 relations from experiment B-2.

Table 5: List of the 20 Highest Nodes of the Activation

	Experiment B-1			Experiment B-2	
	Concept	Activation		Concept	Activation
1	toy1	2.142	1	toy1	2.151
2	motor	1.385	2	switch	1.813
3	spring	1.304	3	switch-on	1.435
4	gear	1.201	4	double-switch	1.263
5	mabuchi-motor	1.174	5	switch6-on	1.263
6	worm & wheel	1.139	6	switch-off	1.245
7	screw	1.124	7	cam	1.238
8	rack & pinion	1.109	8	spiral-spring	1.231
9	fulcrum	1.106	9	upper-switch	1.229
10	board	1.105	10	hand	1.231
11	compress-spring	1.097	11	micro-switch	1.210
12	thread-cutting	1.090	12	gear	1.202
13	ϕ50-gear	1.088	13	motor	1.201
14	20-stroke	1.086	14	lower-switch	1.194
15	1-SUM3-battery	1.082	15	spring	1.186
16	switch	1.077	16	contact	1.160
17	ϕ7	1.076	17	energy-of-battery	1.149
18	cam	1.075	18	chipped-gear	1.144
19	jumping-mech.	1.074	19	lower-switch-off	1.126
20	diameter	1.074	20	lower-switch-on	1.123

Next we build matrix A which represents the semantic network for each experiment, and calculate X from A and C. The program was written in Allegro Common Lisp on a Sun-4 workstation.

We prepare the following two preprocesses before the calculation.

(1) Divide a design process at a regular interval and prepare A and calculate data for each interval. We can see the transitions of the degrees of importance of nodes during the design processes.

(2) If there are nodes connected by either an *isa* relation or an *inst* relation, regard them as a single node. Since a hierarchy tree of nodes is compressed into its root node by this preprocess, the root nodes of hierarchies are highlighted more.

We calculate the data with three different mode, i.e., without preprocesses, with (1) preprocess, and (2) preprocess. We initially set all the elements of vector C to 1 in each mode. This means that all the nodes appeared in the design processes have the same intensity of the constant activation.

4.2.3. Results of the Analysis

First, we calculate the activations of the nodes without preprocess. Table 5 shows the 20 highest nodes and their degrees of the activations. The common concepts in Experiment B-1 and B-2 are *motor, spring, gear, switch* and *cam;* i.e., these concepts are needed and important to design the specification.

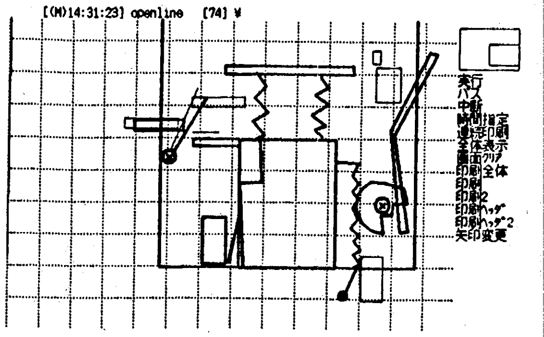

Figure 7: An Example of Drawings in Experiment II-B-2

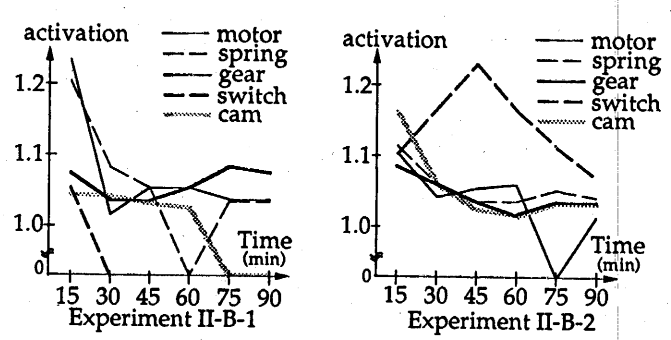

Figure 8: The Transitions of the Activation

Motor, spring and *gear* have bigger values in Experiment B-1 than Experiment B-2 and on the other hand *switch* and *cam* have bigger in Experiment B-2. There are 15 concepts which are subordinate to the *switch* concept in the 30 highest concepts of Experiment B-2. We calculate the activation with (2) preprocess and as a result *switch* concept is the highest by far than the others. When we look at the drawings, we could find that in Experiment B-2 a switch had an elaborated mechanism and play an important role in the toy (see Figure 7). We could also observe that the designers in Experiment B-2 thought the switch was the important part and took enough time to design it. Thus, the degrees of the activation represented the degrees of the attention of the designers and we could see the difference in the attention among the concepts and in particular the parts in the product. Therefore, we can use the degree of the activation to guess the designers' intents that cannot be seen from the drawing or the product itself.

Second, we calculate the activations in the intervals and analyzed transitions of the degrees of nodes. We chose five concepts found as common in Experiment B-1 and B-2. Figure 8 shows the transitions of these concepts. The degrees of the activation of the *motor* concept and the *spring* concept are high at the beginning of the design process, but they decrease rapidly and are low constantly for the rest of the design process in Experiments B-1.[3] On the other hand, the *cam* concept increase at the end of the process. It shows that the designers' attention are shifting from the *motor* and the *spring* to the *cam*. In Experiment B-2, the degree of the activation of the *switch* concept has a peak in the middle of the design process and it is by far higher than those of other concepts. It shows that the *switch* concept, which is one of the most important concept in Experiment B-2, is mainly discussed in the middle of the design process and that during this period it attract most of the designers' thought. Thus, we can see the transitions of designers' attentions using the activation of nodes. This suggests that analyzing transitions is a useful method to know what happened in the design process.

[3] There is a point whose degree is 0. It means there are found no relation on the concept during the interval. We do not take it into consideration because it means nothing but there are no occurrence in the interval.

4.3. Discussion

In this chapter, we have proposed a new method to obtain both verbal and drawing protocol data. And we analyzed this data with the connectionist approach. However, it is is merely one possible method to analyze this data. The data we obtained is huge and scratchy, and in fact contains more various and useful information than we drew here. In particular, most of information on drawings and drawing processes are left to be analyzed.

The method based on the connectionist approach succeeded in the extraction of designers' thought from the protocol data. Using this, we could extract what the designer makes efforts for and how the designer's thought is changing during the design process from the protocol data. We expect more analysis can be done with this method, but some problems are left to be solved.

One of them is that the transformation from the protocol data to the semantic network is voluntary and dependent on the analyst. Although we decided some criteria about how to transform before doing it, they are not enough objective.

CONCLUSION

In this paper, we emphasized the importance of the analysis of design in order to make a rich and useful design theory, and we proposed the *design experiment* which is a practical method to investigate design. It is performed basically by the protocol analysis, and we introduced a new method to record drawings and drawing processes. We examined our method how it can yield useful data from the viewpoint of psychological experiment and the viewpoint of design. We used two methods to analyze the protocol data, i.e., the knowledge extraction and the connectionist approach. Using them, we could see what was knowledge and how it was used in the design process, and focused at the designer's attention and its transition in the design process. Our method enhances the analysis of design processes which is vague and complicated and, therefore, hard to analyze. We believe that both the discussion about the method and the results of the analysis are useful to establish a cognitive model of design processes and furthermore a computational theory of design.

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