A CONTENT-ORIENTED CODING SCHEME FOR PROTOCOL ANALYSIS AND COMPUTER-AIDED ARCHITECTURAL DESIGN

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Abstract. In this paper we introduce a content-oriented scheme for protocol studies of designers and demonstrate its benefit for CAAD research. The structure of the coding scheme is described. We discuss how this method can benefit CAAD research and its differences from the process-oriented method used previously. With this method we analyze data to describe the design process as the combination of sensor-driven and process-driven processes. The results emphasize the importance of the sensor-driven processes in the design process. As a consequence we are able to propose some areas for CAAD tools that are based on the cognitive behaviours of designers.

1. Introduction

Protocol analysis has been widely used to investigate behaviours of individual designers and to examine collaborative design. In most of the literature, concurrent or think-aloud protocols have been used, in which process-oriented coding schemes were utilized. In a previous study (Gero and Tang, 1999), we provided empirical evidence to show the similarities between concurrent and retrospective protocols when using a process-oriented coding scheme. Those results demonstrated that both coding methods produced similar results at the large scale, but there were some differences at the detail level. Also the results provided some cues for establishing computer-aided architectural design (CAAD) tools.

In CAADRIA'99, Wang (Wang, 1999) applied protocol analysis to compare design reasoning when using traditional drawings to that when using virtual reality. The results suggested that the designers who use virtual reality employ experimental archetypes and one-to-multiple or multiple-to-one reasoning. The results were derived from the process-oriented characterisation of design. However, there is an interesting problem triggered by this paper. What are the differences in the visual perceptions of designers when using traditional sketches compared to virtual reality?

In the same conference, Won (Won, 1999) utilized visual data in the design process and questions after the design process to examine the differences in visual thinking between traditional and computational media. This paper applied a content-oriented method that is based on visual information or gestures of the designers. It demonstrated some differences in the characteristics of the perceptions when using traditional and when using computational media.

The process-oriented method, comprising the protocol and the coding scheme, is not sufficient to reveal the cognitive aspects of design. The ability to solve a design problem is not only determined by tacit and explicit knowledge, but also by the designer's personal problem solving strategies and experience. Consequently, there are more and more design studies conducted with interdisciplinary cooperation between designers and cognitive scientists (Pahl, Frankenberger and Badke-Schaub, 1999).

The importance of design cognition research for CAAD research is being established in that its results can provide a foundation for CAAD tools, stimulating the generation of new tools based on human design behaviours. However, how do we study the human design process since we know it is complex and ambiguous? This paper introduces a content-oriented coding method based on the cognitive characteristics of designers. This has the potential to lead to a better understanding of the design process, and as a consequence, we can provide a foundation for the development of CAAD tools that directly support designers.

2. The Coding Scheme

The coding scheme we use was first established by Suwa and Tversky (Suwa and Tversky, 1997) and then developed by Suwa, Gero and Purcell (Suwa, Gero and Purcell, 1998). Using the retrospective protocol approach, it explores the design process by focussing primarily on sketching or sketches and gestures of designers. It is a content-oriented coding scheme. Its structure consists of four cognitive levels of design behaviours: sensory, perceptual, functional, and conceptual levels. This structure distinguishes itself from previous process-oriented coding schemes by its focus on the cognitive aspects of the behaviours of designers and by its focus on the physical and perceptual aspects of the design process. The coding scheme is illustrated in Table 1 (after Suwa, Gero and Purcell, 1998). This coding scheme is concordant with Schon's (Schon, 1985) point of view, so its analysis emphasizes designer's sketching, looking and revising.

TABLE 1. The content-oriented coding scheme

Level	Content	Description
Physical	D-action	Drawing and looking at the concurrent depictions
	L-action	Looking at previous depictions
	M-action	Other physical actions
Perceptual	Emergent spaces	Perceiving the implicit spaces between depictions
	Visual features	Perceiving shapes, lengths and textures of depictions
	Spatial relationship	Perceiving proximity, alignment, intersection between depictions
Functional	F-action	Assigning non-visual information or meanings to visual depictions or perceptions
Conceptual	Setup of goals	The intention designers want to achieve
	Make decisions	Deciding the positions, arrangements and design requirements

3. The Experimental Process

The experimental process in this study was originally designed by Suwa and Tversky (Suwa and Tversky, 1997), and consists of two parts. Part one is a design task, in which the architects design (a small art museum in this case) with detailed requirements described in the instructions. For the art museum these requirements include a sculpture garden, a pond, a green area and a parking lot. The subject receives a simple diagram representing the outline of the site. One camera is utilized to record the designer's behaviours in the design process, and afterward the videotape is utilized as visual cues for retrospection. In part two, the subject retrospectively reports the design process with the aid of the videotape. He/she is asked to report every thought regarding each stroke in the sketches.

The utterances during the retrospection are transcribed into text word by word. The entire protocol then is separated into small units, segments, by interpreting the way in which concepts shifted in the designer's mind. A segment consists of pieces of coherent information. The information consists of the related utterances and actions. Sometimes the sequence of the retrospective protocol has to be rearranged according to the behaviours and intentions of the designer.

In each segment, the number of components at the four cognitive levels depends on the corresponding behaviours of the subject. Importantly, each component has inter-linked relationships with other components in different levels. For example, the perceiving of visual features is dependant on the L-action of one previous depiction. Furthermore, some segments maybe associate with previous segments by revising previous depictions. The design process is transferred into a composition of inter-linked levels and segments.

The data produced by this method is different from that in previous protocol studies in two ways. First, the method requires subjects to report every stroke and related thought unless he/she can not recall them. Second, the experimenter or the subject can stop the videotape if the report lags behind the design process. Consequently, the subjects report more information about physical and perceptual aspects than other kinds of methods. We report data from a single architect here.

4. Understanding Design Using the Content-Oriented Approach

Lloyd, Lawson and Scott (Lloyd, Lawson and Scott, 1995) proposed that the design process is a combination of many interlocking and overlapping processes. They presented two ideas. First, the design process is not a unitary thing, but a collection and pattern of many things. Second, concurrent protocols can only effectively reveal verbal thought in the design process. Triggered by their ideas, some questions are proposed here for CAAD developers. What kind of design processes is recognized when CAAD developers design the tools? Is it a unitary information-processing process or an interlocked and inter-related combined process?

We do not provide the answers to these questions, but describe a method that can be used in exploring these questions for CAAD developers. Followed an outline of four aspects of the design process, we discuss what the content-oriented scheme can reveal about these areas and what influences can the results bring to CAAD developers. To simplify the terms, we use "C-method" to mean the content-oriented coding scheme generally used in retrospective protocols and "P-method" to mean the process-oriented coding scheme generally used in concurrent protocols.

4.1. NONVERBAL THOUGHT IN THE DESIGN PROCESS

According to Lloyd, Lawson and Scott's observations, nonverbal in design thought is a form of abstract activity that is accompanied by sketches. Given the separation between designing and reporting and the emphasis on sketches, the nonverbal thought associated with sketches could be revealed without interference. The subjects have enough time to report what he/she thought, and report more about the visual thoughts in the design process. They are seldom found in a P-method. Two examples are elicited to show how the C-method can reveal nonverbal thoughts.

> *Segment 13. 00:03:05. Then I was trying to develop a real form of the building. So I drew this line to see this is one space, then drew this line to see this is another space, this some kind of intermediate space, So I thought this was the most important space since the road is here.*

Segment 20. 00:05:30. Now I saw this line, trying this line, trying to give some kind of relationship between this line and this line, So I kind of cut the corner of this building to give more definition to this area also. When you point something like this, it does not give anything to this area, whereas cut the corner give some kind of definition to the area of there.

We can see from these segments and the related actions in the videotape that nonverbal thoughts about sketching, looking, and the relation to intentions are revealed, at least in part. Moreover, we can explore how designers draw and perceive by applying the content-oriented coding scheme. For example, we identify three D-actions, one L-action, and four perceptual actions in segment 13, and identify 2 D-actions, four L-actions, and two perceptual actions in segment 20. They are very rich material to understand the nonverbal thought in each segment of the design process.

For CAAD nonverbal thought should be the key area in supporting the conceptual design process. How designers draw and how designers perceive their sketches when using CAAD tools should be understood before we design them. Until now, CAAD tools are largely absent in the conceptual design stage. This method can describe the appearances of D-actions and L-actions and the relations between them and conceptual thought, so we are able to investigate the differences in design behaviours when using freehand sketches and using CAAD tools. The answers have the potential to provide the cues to modify the tools and the boundary of CAAD support.

4.2. VERBAL THOUGHT IN THE DESIGN PROCESS

Lloyd, Lawson and Scott regard the periods when designers exhibit problem-solving behaviours as the times when the concurrent protocol is close to the subjects' thought, namely verbal thought. In this respect, the C-method has advantages in the amount of information it can produce because of the unrestricted time of reporting. Retrospective protocols are not so time-dependent as concurrent protocols, implying that the reporting time does not correspond to the progress of the design process, so the relationship between the design process and time could not be accurately observed. There may be nonlinear order in retrospective protocol due to the mixture of memories. Under these circumstances, the data has to be reorganized according to the content and designers' intention.

4.3. PERCEIVING THE DESIGN PROBLEM

The first perception of the design situation a designer has is often recognized as the primary generator (Darke, 1979). It affects the way a designer deals the design situation.

4.4. MOMENTS OF INSIGHT

When the existing knowledge and the problem situation a designer faces are brought together by the designer to produce an unexpected result, that moment is called “an insight” or an “a-ha phenomenon” occurs. The C-method is capable of revealing this moment that is directly related to creativity issues. For instance, when our designer tried to arrange the inside spaces of a museum, he suddenly found a gap between his previous depictions of two rooms. He realized this gap could be regarded as a gate for visitors leaving the museum. He reported:

> *Uhh, I say, this looks like a small gap. Maybe people can go out from there.*

Then, he decided the inner route of the museum. Encoding it by the content-oriented scheme, we re-describe the process as follows. The designer examined his existing drawings (L-action), and suddenly found the relationship of two old depictions (perceptual). He realized this gap could be used as the gate for visitors to leave (functional), so he decided to do so (conceptual/making a decision). As we can see, the C-method can help us to explore the process of the occurrence of an insight. These insights are called “unexpected discoveries” (Suwa, Gero and Purcell, 1998). Many researchers believe the occurrence of insights is the key to creative design, but there have been no adequate tools to observe it. With this method, we have the capacity to examine the process and even distinguish what aspect CAAD tools need to have to support the appearance of insights.

To sum up, the benefit of utilizing the C-method for CAAD is to have tools to examine nonverbal thought and insights that CAAD tools should be able to support. By this method, we are able to examine the design process from a cognitive point of view, instead of a purely computational or information-processing viewpoint. The research results can stimulate CAAD developers to produce different tools from a different foundation.

We regard the design process as being composed of interlocking and interwoven processes among four different cognitive levels. We found concurrent CAAD tools can support some physical aspects of design. They can produce functional and conceptual suggestions using knowledge-based or case-based AI software. However, there is very little software that can stimulate the perception of designers to produce new images from previous depictions that will lead to changes of visual features and relationships and functions.

5. Sensor-Driven and Goal-Driven Processes

We found distinguishable processes to substantiate our assumption that design is a combination of different processes. The first process could be regarded as a bottom-up process driven by the sensory data. Designers carry out their communication with sketches by D-actions for new depictions or with L-action for old depictions. They sketch to visualize thoughts as sensory data, and revise the existed depictions to have more sensory information. The sensory input, mainly from sketches, is then perceived by designers as implicit spaces, visual features or relationship between depictions as perceptual inputs. They are conceptually associated with non-visual meanings to be manipulated as functional issues.

The sensor-driven process co-exists with a top-down process driven by conceptual data. In order to achieve the goals or decisions, designers reason about related functional issues and associate them with old or new depictions and perceptions. These physical and perceptual elements are manipulated to test the conceptual ideas. If the idea is feasible, the depictions are preserved; if not, designers modify the conceptual idea or related depictions.

Two instances are given from the protocols. First, at 43 minutes into the design session, the designer looked at the sketches and reported:

> *Trying to see what kind of relationship this (p: the slope of the roof at the entrance) gives to this, create some kind of tension. That's why……*

Here he initially tries to "see" something from the existing depictions without the interference of knowledge or conceptual reasoning, then he perceives the visual relationship, and finally reasons about the circulation within the site. This shows the relationship between the designer's action/seeing and the content of the design process. The sensory input triggers the perception, and then functional references occur. Second, at 10 minutes, the designer tried to arrange the circulation in the site and reported:

> *I was also thinking of circulation within the site, say, you enter here, going to the exit around here, making two roads, I was thinking to ….*

In this instance, he initially set up a conceptual goal to figure out the circulation problem within the site, and then he perceived a visual relationship to realize his conceptual thought. It shows the relationship between the content (the roads and the on-site circulation), and a component of the design process (the goal to solve the circulation). The conceptual set-up of goals triggers the functional reference and then the designer perceives a visual relationship to realize the thought.

These map onto goal-driven and sensor-driven processes in terms of design cognition.

We find that two paradigms regarding the design process are appropriate to describe these two processes individually (Dorst and Dijkhuis, 1996). The information-processing view describes the design process as different state spaces (goals) consecutively fulfilled in order to reach the final goal, highlighting the relationship between the content and the components of the design process (Simon, 1992). In contrast, the reflection-in-action view emphasizes the seeing and receiving by designers to reframe the design problem, highlights the relationship between the content and designer's actions (Schon, 1995). Both paradigms possess essential qualities of the design process, and are adequate to capture the peculiar characteristics of sensor-driven and process-driven processes. As a result, we can regard the design process as the mixture of sensor-driven and goal-driven processes illuminated through the C-method. Importantly, we can examine these two paradigmatic views in one single method.

We calculated the number of sensor-driven and goal-driven segments in our data. In this data, 30 percent of the total segments are sensor-driven. This means the designer depends heavily on the sketches to advance the design process since the processes are triggered by D-actions or L-actions that are directly related to sketches. The P-method analysis and CAAD have ignored this part.

In the goal-driven process, CAAD tools have produced numerous and powerful tools to either present the results or provide design knowledge to help designers make decisions. Two-dimensional and three-dimensional computational representations and virtual reality have been useful for designers to represent their thoughts. However, there are very few tools that can aid the sensor-driven process in the design stage.

6. Sensor-Driven Processes and CAAD Tools

We examined the physical actions that trigger the sensor-driven process in order to discuss how CAAD tools can aid these processes. The differences between what triggers the sensor-driven process and what CAAD can provide may demonstrate the deficiency of current CAAD tools.

Table 2 presents the times spent and the percentages of the various actions triggering sensor-driven processes during this design process. The abbreviation Dc stands for designers' creating a new drawing, Drf for revising a visual feature, Dsy for drawing symbols to intensify concepts, Dwo for writing verbal memos, Dts for tracing depictions in the same sheet, and Dtd for tracing depictions in a different sheet. L-actions occur when there is no D-action but L-actions trigger the sensor-driven process. In some sensor-driven processes there is more than one D-action.

TABLE 2. The actions triggering sensor-driven design process

Types of actions	Dc	Drf	Dts	Dtd	Dsy	Dwo	L-actions
Times	14	4	26	0	10	4	4
Percentage	23%	6%	42%	0%	16%	6%	6%

Dts and Dc have very high incidences. Designers use them to bring different depictions into focus and modify previous depictions in sketches. The high proportion of these two actions proposes questions for CAAD tools. How to make these actions feasible in CAAD tools? How to group depictions more easily especially when designers try to group two visual elements belonging to two different groups. Take as an example the case where the designer saw the intermediate space between two squares, and tried to group one side of each squares and the middle space, Figure 1.

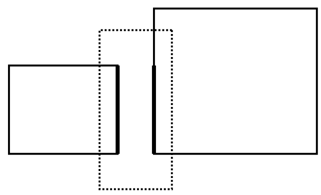

Figure 1. The dashed lines indicate the designer's focus

7. Discussion

The issue arises as to whether CAAD tools can provide similar properties as freehand sketches in order to stimulate the generation of unpredicted perceptions that can then result in insight during the design process. Suwa, Gero and Purcell (Suwa, Gero and Purcell, 1999) proposed that the combinations of previous drawings and observing the sketches from a different meaning are two ways of triggering the occurrence of unexpected discovery. The first one is called a sensor-driven process. In this study, we can see the benefits of using freehand sketches, but why can freehand sketches provide these benefits? From our analysis, we suggest two reasons. Freehand sketches are ambiguous, so designers can redrew previous depictions to change the shapes or positions little by little to test their thoughts. This is the computational equivalent of changing the underlying representation. Also, human re-representation along with sketching, is fast enough to match the speed of thought. In a previous study, we have shown how fast the focus of a designer changes (Gero and Tang, 1999).

This paper demonstrates the abilities and advantages of the C-method, a method that has not been widely utilized in examining design. Although based on a very small number of experimental results, this paper sheds light on the areas CAAD tools need to work. There are many research issues arising from here. For example, what are the differences of perceptions when using sketches and CAAD tools? Can CAAD tools provide help for designers' physical and perceptual actions like freehand sketches? Do CAAD tools interfere with sensor-driven processes? All these questions rely on this method as a research tool to explore and find some answers.

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