CAADRIA2001
John S. Gero, Scott Chase and Mike Rosenman(eds),
Key Centre of Design Computing and Cognition, University of Sydney, 2001, pp. 81-89.

ROLES OF KNOWLEDGE WHILE DESIGNING AND THEIR IMPLICATIONS FOR CAAD

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Abstract. This paper outlines some roles of knowledge while designing based on experimental results from studying novice and expert designers. The implications of these experimental results on future CAAD systems are discussed.

1. Design Knowledge

The architectural design process can be categorized using various types of knowledge. Both qualitative and quantitative aspects of design knowledge are difficult to examine because of the varying definitions of knowledge itself. A number of knowledge-based design systems in computer-aided architecture design (CAAD) have been proposed and some of them are based on observations or retrospection of designers. However, there is still some distance from practical design knowledge to that included in computational models.

Architectural design knowledge reuse requires it to be generic. This study examines the roles of design knowledge from the perspective of cognitive psychology in an attempt to provide some empirical data on design knowledge. The implications for knowledge-based CAAD are examined.

In a recent study, Varejão et al. (2000) proposed an ontological framework for knowledge-based design systems in order to minimize misunderstanding and miscommunication in computer-aided design. This structure includes design requirements, artifact descriptions, and importantly the designing process in which five major design activities are applied in manipulating knowledge and generating end products. This very detailed structure of design knowledge raises a question: whether physical and perceptual aspects of the designing activities affect the

accumulation and modification of design knowledge. Is it possible that some aspects of design knowledge are missing in their structure?

2. Experiments and the Coding Scheme

In order to observe some general features of design knowledge, we conducted some cognitive experiments in which architectural experts and novices designed a residential house in a Sydney suburb. After the design session, they retrospectively reported on their designing process using videotapes of their design session. The design session commenced with the actual information and photographs of a fully serviced home site surrounded by a large recreation reserve. The background and requirements of clients were included. Participators had 50~70 minutes to finish conceptual designing, and then they were required to retrospectively report their thinking process. Subjects watched the videos recorded in their design session as visual and memory aids, and provided verbal data without interference with the design process.

The retrospective report session was transcribed into a raw protocol, and it was parsed into segments based on the designer's intentions. Intentions are the smallest units of design reasoning present or the smallest sensible statements about the design or aspects of it (Goldschmidt, 1991). Thus, we encoded the protocol based on verbal transcripts, videos, and the designers' sketches in order to capture the content and context of designing activities. We applied the same methodology here that has been presented in a previous CAADRIA paper (Tang and Gero, 2000).

To include the actions in the examination of the design knowledge, we applied the cognitive coding scheme that accounts for four levels of design behaviours (Suwa et al., 1998). This scheme includes:

- physical
- perceptual
- functional and
- conceptual

levels that correspond to processes claimed for human cognitive information processes. As a result, this study observes design knowledge with other major designing activities including the following:

- sketching
- looking
- moving
- seeing and
- perceiving

in a complete design process.

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The higher-level cognitive activities are divided into functional references and conceptual reasoning. Functional references are the meanings attached to depictions by designers. It is common in the design process that designers annotate their depictions to indicate the meanings, and previous study demonstrated that this is a way to externalize thoughts (Suwa et al., 1998).

Conceptual reasoning is categorized into four elements drawn from the literature, empirical observations, and the encoded data.

- **Setup of goal** is the requirements of design a designer intends to achieve or the requirements of design that has been achieved, for example, encoded as setup of goal is a segment in which the designer tries to design a better circulation.
- **Expertise** is a designer's knowledge about how to do design in a circumstance. This kind of knowledge is not given in the brief, but it constraints the design space or solves a design problem. For example, how to achieve the general set back distance of a residential house that is defined by the local council.
- **Evaluation** is the knowledge used to judge the quality and feasibility of what is depicted in the sketches related to functional issues. For example, a designer thought about the size the studio being much bigger than the living room as was required by the brief.
- **Design strategy** is the knowledge transiting the design stage from one to another to advance the designing process, and it is generally learned in design schools. For example, a designer placed measurement scales after producing the bubble diagram.

3. Results

3.1 DECLARATIVE AND SCHEMAS

In cognitive psychology, there have been debates about what sorts of knowledge representations are appropriate. Anderson (2000) divides them into two types. Perception-based representation attempts to preserve much of the structure of a perceptual experience. Meaning-based representation attempts to abstract out some significant aspects of an experience. In the design research community, when knowledge is referred to it is generally only meaning-based. However, it may be the perception-based representation that makes the design process so different from other activities. The unique features of design knowledge have obvious influence on design thinking, education and computational tools.

Most of the knowledge-based and case-based CAAD systems depend on static expertise in specific domains. They are meaning-based knowledge representations. Cognitive psychologists categorized them into declarative and procedural knowledge. The former includes all explicit knowledge of various facts of the world, while the latter includes how to perform various tasks based on declarative knowledge. Anderson (2000) proposed detailed structures of them as propositional networks and schemas.

Our encoded protocol shows that, in terms of declarative knowledge, the experts produced more complete lists of requirements regarding the design than the novices did. Although our design brief provided details functional requirements, the experts produced their own checklists regarding different aspects of residential houses. One interesting finding in our experiments is that we inadvertently omitted the specific requirement for a toilet and every expert detected the lack of the toilet in the requirements and expressed concern about it. However, this detection did not happen in any novices' designing processes. It may be so that novices would have found this missing requirement with more time, but the experiment showed that the knowledge that practitioners use is different from that of novices.

Moreover, the issues experts were concerned with in these experiments were much richer than those outlined in the design brief and were also much richer than the novices' concerns. For example, the concern about building materials and council restrictions were important in the experts' design processes, but not so in the novices' processes. It is claimed that this rich knowledge enables experts to cope with design problems more effectively and efficiently. In 45 minutes, all our experts finished the design with many scaled details. Some very experienced designers appeared to simply describe the design on the papers without apparent thinking at all. Their design quality however was obviously better than the novices'.

In terms of procedural knowledge, our empirical data shows that the experts had more organized and longer scripts to control the design process. Different experts had different ways of approaching the design. For instance, some preferred to synthesise and reason about the requirements alternatively, while one expert, being also a senior lecturer of design, preferred to list all the requirements before drawing. All of them could control the design process more effectively than the novices did. They finished their designs on time and checked their progress a couple times to make sure they could finish on time. The experts applied previous goals and functions more often than the novices did, so the experts' efforts were more effective and efficient. This phenomenon was demonstrated by two types of setup of goal in our experts' encoding

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being richer than novices'. They were, first, applying previous introduced arrangements in current context, and, second, repeating or continuing previous goals.

3.2 CONNECTIONS WITH ACTIONS

Given that the structure or representations of knowledge in design is the same as that in general knowledge, it is proposed that the content of knowledge involved in the design process is different from those in other disciplines. Cross (1982) pointed out that the uniqueness of design knowledge distinguishes design activities from scientific and artistic ones. It is "designerly ways of knowing". Design has its own distinct "things to know, ways of knowing them, and ways of finding out about them".

From the analyses of experimental data, we found one of the ubiquitous features of design knowledge: the interactions with actions. In our analytical structure, some goal setting and evaluations were different from the static types of knowledge, such as expertise and design strategies. The static ones were not related to physical and perceptual actions, being able to be isolated. In contrast, some goal setting and evaluation were closely connected to physical and perceptual actions. For them, the process in each segment was either top-down or bottom-up via different cognitive levels. These higher-level cognitive activities cannot be isolated and separated from other actions. For example, the setting up of a goal to fulfil the initial requirement led to the drawing actions that put a corresponding shape on the paper. By contrast, in evaluation designers justified the existing drawings through seeing, a physical action.

Design strategies and expertise were embedded in the higher-level reasoning process. We found that the former was applied to guide the flow of the design process and checked the current situation. It was the methodologies that designers learnt during their education. The latter was like the if … then … statements in the designers' minds, helping designers to solve pre-existing problems and relieving workload.

3.3 PASSIVE AND ACTIVE

The expertise and design strategies found in our data were the design knowledge regarded as static and predetermined in designers' minds. They were proposed when the designing process was regarded as a pure information-processing process. Design knowledge was grouped into different packages, in which the relevant knowledge about one design unit and how to use it were embedded. Each package was a schema forming a hierarchical organization (Akin, 1979). Following the same vein, each

"space" and "move" in the design process was dominantly determined by the knowledge, like problem solving reasoning or information processing.

However, some research suggests that design knowledge is not entirely passive. For example, one kind of knowledge can integrate different parts of knowledge, transforming the contradictory situation into a meaningful and coherent design. This feature has been studied as the "primary generator" or "organizing principle" (Darke, 1979). Recently, Gero (1999) proposed that knowledge in the designing process is not only passively providing information to advance the design process, but actively developing the designing process to know. In the same vein, Heylighen et al. (1999) proposed that the designing process could be described as the oscillation between passive knowledge and active knowing in a dynamic balance. They examined the design activities in a studio environment to show that the action knowledge and action each dissolve and blend into a "knowing in action", and compared the dichotomy of design knowledge as concept/component or passive/active pairs.

This study proposes that one important role in design knowledge should be reserved for actions. Actions help designers to actively know the design problem and situation, and by various physical and perceptual actions they aid designers to realize and evaluate design ideas. The oscillation between lower-level actions and higher-level reasoning accumulates the active knowledge. When designers face a similar problem next time, the existing knowledge is passively utilised to solve the problem.

An empirical example that we could find in our data is that of goal setting, a goal to apply previously introduced functions or arrangements into the current context as a requirement. The example is as follows. A designer initially created a kitchen window inadvertently so the residents could look out when cooking, and he found the idea very good and applicable. Drawing the next sketch, he remembered the kitchen window and "wanted" to create a "look out" window in the kitchen. This was a process in which knowledge was transferred from being active to passive.

3.4 THE ROLES OF DESIGN KNOWLEDGE

In a recent paper, Tversky (1999) proposed that the representations, segmentations, and orders of depictions reveal the organization and components of underlying conceptual elements. Drawings are clues to conceptualizations of mental domains, and studying the segmentations and orders of sketches in design should give insights into operations and schemas of conceptual modules. Consequently, both lower-level and

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higher-level cognitive activities are related to design knowledge through functional issues.

From a macroscopic view, the encoded results indicate that design knowledge plays three important roles in the designing process.

- Design knowledge is the determinant of the concept-oriented processes. It is the process that occurs in a segment and is driven by decision-making or the set-up of a goal. Set-up of a goal determines the process in each concept-driven segment, and activates drawing and looking actions. Expertise is beneficial in generating solutions in segments, and in reducing "trial and error". Both of them direct the concept-oriented processes.
- Design knowledge is an examiner of the sensor-oriented processes. It is the process that occurs in a segment driven by sensory actions. This kind of design knowledge is evaluation: evaluating the match between the concept and the interpretation of the drawing, and evaluating the aesthetic and functional usability of that interpretation
- Design knowledge is the strategic connection between different design stages. Different design strategies, such as the bubble diagram and concept production, generate different kinds of sketches and subsequent perceptions. They connect different kinds of segments, and make the intuitive generative process appear more systematic and controllable.

The results here are different from previous research in that design knowledge is significantly related to physical and perceptual activities. Consequently, the design process is a meaning-rich and reasoning process embodying various external actions. The end product of design still has to fulfil many other functions such as marketing and usability.

4. Implications

Current CAAD systems are beginning to utilise knowledge-based tools including declarative and procedural aspects of meaning-based design knowledge. In contrast, the perception-based design knowledge system still needed to be developed. Our analysis implies that CAAD systems should included graphical representation as an entry to the database. The geometry and topology of sketches should provide cues for searching relative expertise because of the close connection between the perceptual actions and design knowledge. Other kinds of design actions should also be useful when determining what kind of knowledge is needed. For example, the annotations of specific sketches can be used to link to existing knowledge to their depictions (Gross et al., 1994; Gross, 1996). Similarly, the depictions can guide the knowledge system's search for related

information. However, our previous study indicates that speed and timing are very important in providing proper aids at the proper time (Tang and Gero, 2000).

In terms of active design knowledge, the next generation of CAAD systems should provide learning mechanisms that can change the strategic knowledge according to the situation. This kind of situated computational system is currently being studied (Gero, 1999; Gero and Fujii, 2000; Saunders and Gero, 2001). The self-modification of this kind of situated CAAD system has the potential to benefit designers when it can follow the change of the designer's design knowledge. It could be treated as a personal assistant, and its motivation or interest is from the user and user's behaviours.

Acknowledgements

This research is supported by an Overseas Postgraduate Research Scholarship and in part by a grant from the Australian Research Council.

References

Akin, Ö. :1979, *Models of Architectural Knowledge: An Information Processing View of Architectural Design*, University Microfilms International, Ann Arbor, Mich.

Anderson, J. R.: 2000, *Cognitive Psychology and Its Implications*, Worth Publishers. New York.

Cross, N. :1982, Designerly ways of knowing, *Design Studies*, **3**(4), 22 1-227.

Darke, J.: 1979, The primary generator and the design process, *Design Studies*, **1**(1), 36-44.

Gero, J. S.: 1999, Recent design science research: Constructive memory in design thinking, *Architectural Science Review*, **42**, 3-5.

Gero, J. S. and Fujii, H.: 2000, A computational framework for concept formation in a situated design agent, *Knowledge-Based Systems*, **13**(6), 361-368.

Goldschmidt, G.: 1991, The dialectics of sketching, *Creativity Research Journal*, **4**(2), 123-143.

Gross, M.: 1996, The Electronic Cocktail Napkin - computer support for working with diagrams, *Design Studies*, **17**(1), 53-70.

Gross, M., Zimring, C. and Do, E.: 1994, Using diagrams to access a case library of design, *in* J. Gero (ed.), *Artificial Intelligence in Design'94*, Kluwer, Dordrecht, Netherlands, pp.129-144.

Heylighen, A., Neuckermans, H. and Belgium, J. E.: 1999, Walking on a thin line – between passive knowledge and active knowing of components and concepts in architectural design, *Design Studies*, **20**, 211-235.

Saunders, R. and Gero, J. S.: 2001, Designing for interest and novelty: Motivating design agents, *CAAD Futures 2001*, Eindhoven, (to appear).

This is a copy of Tang, H and Gero, JS (2001) Roles of knowledge while designing and their implications for CAAD, in JS Gero, S Chase and M Rosenman(eds), *CAADRIA'01*, Key Centre of Design Computing and Cognition, University of Sydney, 2001, pp. 81-89.

Suwa, M., Purcell, T. and Gero J. S.: 1998, Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions, *Design Studies*, **19**, 455-483.

Tang, H.-H. and Gero J. S.: 2000, Content-oriented coding scheme for protocol analysis and computer-aided architectural design, *in* B.-K. Tang, M. Tan and Y.-C. Wong, (eds), *CAADRIA2000,* CASA, Singapore, 265-275.

Tversky, B.: 1999, What do drawings reveal about thinking? *in* J. S. Gero and B. Tversky (eds), *Visual and Spatial Reasoning in Design,* Key Centre of Design Computing and Cognition, University of Sydney, Sydney, pp.93-101

Varejão, F. M., Menezes, C., Garcia, A., Souza, C. and Fromherz M.: 2000, Toward an ontological framework for knowledge-based design systems, *in* J. S. Gero (ed.), *Artificial Intelligence in Design '00,* Kluwer, Dordrecht, Holland, 55-75.

This is a copy of Tang, H and Gero, JS (2001) Roles of knowledge while designing and their implications for CAAD, in JS Gero, S Chase and M Rosenman(eds), *CAADRIA'01,* Key Centre of Design Computing and Cognition, University of Sydney, 2001, pp. 81-89.