# Cognition-based CAAD

*How CAAD systems can support conceptual design*

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Abstract: This paper introduces the concept of cognition-based CAAD. Protocol analysis and a content-oriented coding scheme are utilised to produce cognitive results of designers' behaviour. This empirical analysis suggests that the speed of thought and vagueness among actions are the main areas to be supported by any cognition-based CAAD system. Three different modes of design thinking are presented as the basis of a possible CAAD system.

## 1. INTRODUCTION:

Current commercial CAAD systems focus on representations and manipulations of those representations with a small number being able to deal with information processing views of designing (Gero, 2000). This paper proposes that, from a cognitive point of view, perception, functional references, and inter-linked relationship between high and low cognitive levels should be integrated into CAAD systems to produce a cognition-based CAAD system. We utilise empirical results obtained by examining designing behaviours of expert and novice architectural designers to substantiate our assumptions. The results imply that these areas should play important roles in future CAAD systems in order to allow them to be used during conceptual design. The empirical results are based on protocol studies of an expert and a novice designer. The remainder of this paper describes the experiments and the results and places them in the context of a potential CAAD system.

## 2. METHODS

Protocol analysis is utilised to examine the design processes in order to provide information for a cognition-based CAAD system. Recently, retrospective protocols has been used in several studies to explore human design activities because of the claim that they minimise the interference they cause to the designers. This study follows the same method in which participating designers first design for the designated brief, and then retrospectively report the design process with the aid of the videotapes of their designing in the first phase.

The oral report is transcribed into a raw protocol. Utterances, sketches, and videos are the material by which researchers examine and understand the design behaviours and encode the protocol. The encoded protocol is organised into information processing streams, documenting which types of information and how they have been processed in terms of our coding schemes.

The analytical structure of this coding scheme consists of two primary levels. Lower level cognitive activities contain physical actions and perceptual actions that interact with the outside world, including drawing, looking, and recognising graphical features and spatial relationships. Higher level cognitive activities contain functional references and conceptual actions that interact with the designer's internal world, including functions, views, setting up goals and making decisions.

This coding scheme was originally established by Suwa and Tversky (Suwa and Tversky, 1997; Suwa, Gero, et al., 2000), and applied by Tang and Gero for their series of studies (Tang and Gero, 2000). It represents the design process in terms of four inter-linked and inter-related types of cognitive actions – physical, perceptual, functional, and conceptual actions in each segment. An episode of the design process is constructed by a series of consecutive segments. These segments represent the smallest units of intentions of a designer. All the four types of cognitive actions in one single segment have relations but no chronological order.

## 3. CONCEPTUAL DESIGNING

Conceptual designing occurs when the designer is trying to understand the problem and set the situation for the following processes. It does not mean that the designer does not exhibit similar features during the remainder of the design process, but conceptual designing is the period having the richest range of ideas, problems, and creativity. However, current CAAD systems seem to be absent from this design process, and most designers still conduct their conceptual designing using hand-drawn sketches, or more romantically on the back of an envelope.

Given that CAAD systems should have the capacity to support this design phase to provide a holistic design process, from concept generation to manufacture, this study examines what CAAD systems should support in order to support designers during conceptual designing.

## 3.1 Speed of shifting intentions

We assume that the protocol is divided according to the designers' intentions, instead of verbalisation events or syntactic marks (Ericsson and Simon, 1993). This has been applied in recent protocol studies in which designers' intentions are understood not only through the verbal utterances but also through their drawings and gestures (McNeill, Gero, et al., 1998)). In the same sense, one segment consists of pieces of information, which appear to have occurred simultaneously in the designer's mind, and constitute a set of coherent cognitive actions – physical, perceptual, functional, and conceptual. Thus, segments are the representation for the designer's intentions, and the speed of shifting intentions represents the speed of thought and related actions.

In our empirical data, shown in *Table 1*, the expert's encoded protocol consists of 338 segments with an average time span of each segment of 8 seconds, whereas the novice's encoded protocol consists of 145 segments with an average time span of 20 seconds. The experimental duration was 45 and 48 minutes respectively.

*Table 1.* Number of segments and average time span of the novice and the expert

| | Number of segments | Average time span (seconds) |
|---|---|---|
| Novice | 145 | 20 |
| Expert | 338 | 8 |

The result indicates that this expert shifted his focus from one topic to another on average every 8 seconds, and the novice did so every 20 seconds. Given that the speed of shifts represents that of thought, it is much faster than was expected. In terms of using a CAAD system, the time this expert took to shift his focus was of the order of that for a user to pull down a menu, select the function, and input parameters.

The surprisingly fast speed of change of topic during conceptual designing provides a basis for why designers still prefer using pen and paper even when they have expensive, powerful, and cutting-edge CAAD systems, during conceptual designing. It is simply because these familiar sketching skills can catch up with the speed of thought, the speed of ideas, and the speed of creativity. The speed here is not relevant to computational power nowadays because even the latest CAAD system cannot efficiently support this design phase. The problems are that the interface between designers and machines is not sufficiently intuitive and simple enough to follow the train of thought so that the use of a CAAD system blocks the development of thought and ideas. It results in spending too much time on the software rather than on designing.

## 3.2 Speeds of physical, perceptual, functional, and conceptual actions

In our encoded data, every segment consists of four different kinds of actions, but the number of actions in a segment depends on the content of that segment. For example, one segment may have 4 physical actions, 2 perceptual, 3 functional, and 1 conceptual, while the following one may have only 2 physical and 1 perceptual actions.

"Physical" refers to actions that have direct relevance to depictions via drawing, revising or gesture. "Perceptual" refers to actions that attend visuo-spatial features or relations of depictions with or without physical actions. "Functional" refers to the actions that attach functions and abstract concepts in depictions or visuo-spatial features and relations. "Conceptual" refers to the actions that manipulate functions and abstract concepts through setting-up goals, aesthetic evaluation, and design knowledge. These four actions and their relations capture the essence of the cognitive processes of design thinking.

*Table 2* and *Table 3* show the basic statistical descriptions of each type of actions in our novice and expert's encoded data. The results indicate that on average the novice has 3.6 physical and 1.5 perceptual actions every segment, which spans 20 second on average. Whereas the expert has 3.1 physical and 1.8 perceptual actions every segment, which lasts 8 seconds on average. These external action rates were measured when designers were using pen and paper.

*Table 2.* Basic Statistical Description of actions in the novice's encoded protocol

| | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|
| Physical action | 3.6 | 2.3 | 0 | 15 |
| Perceptual action | 1.5 | 1.2 | 0 | 5 |
| Functional action | 1.9 | 1.6 | 0 | 7 |
| Conceptual action | 0.8 | 0.5 | 0 | 2 |

*Table 3.* Basic Statistical Description of actions in the expert's encoded protocol

| | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|
| Physical action | 3.1 | 1.5 | 0 | 8 |
| Perceptual action | 1.8 | 1.1 | 0 | 6 |
| Functional action | 2.3 | 1.6 | 0 | 7 |
| Conceptual action | 0.8 | 0.8 | 0 | 4 |

The average numbers of all actions in every segment further emphasises the rich information processing that occurs during conceptual designing. According to this result, it is hard to image how designers can use current CAAD systems during conceptual designing. For example, in 20 seconds how may operational actions can a novice finish in a CAAD system whether using pull-down menus or short-cut keys or not. In terms of cognitive load of human memory (based on the ‘magic number seven’ for short term memory capacity), there is very little capacity left for designers to use the tools if we intend to maintain the same speed. As a result, a cognition-based CAAD system would be one with a very simple and intuitive interface without many selections and pull-down menus.

Moreover, examining current CAAD systems from the perspective of these four actions, we can find that most CAAD systems focus on two actions: drawing in physical actions and design knowledge in conceptual actions. The former are representational kinds of CAAD systems, such as AutoCAD and ArchiCAD, with their emphasis on the scaled details and presenting all the components in a two- or three- dimensional world. The latter ones are knowledge-based or case-based CAAD systems, providing designers possible and useful design knowledge. Very few systems are capable of supporting a designer’s perceptual and functional actions. However, they are as important as drawing and design knowledge in terms of frequency of appearance during conceptual designing.

## 3.3 Vagueness

Vagueness and uncertainty of depictions and their relations with other types of design activities during conceptual designing are the other feature resulting in the failure of current CAAD systems to adequately support this preliminary design process. Goel (1999) regarded this feature as the characteristics of ill-defined representation, being imprecise, ambiguous, fluid, indeterminate, etc.

Drawing in physical actions are the foundational and most frequent activities according to our analytical results. All the actions are relevant to or based on drawing and sketches; Schön and Wiggins have long described the design process as the reflective and conversational process between designers and sketches (Schön and Wiggins, 1992).

Most of the sketches during conceptual designing are like *Figure 1* in terms of vagueness. In these sketches, depictions are syntactically uncertain, ambiguous, overlapping one with another, and scale-wise unfixed. Numerous shapes and spatial relations could be generated from an arbitrary combinations of these depictions. These qualities help designers create lateral transformations of ideas for creative problem solving in Goel's terminology. In terms of CAAD systems, the syntactic disjointness and differentiation of drawing systems, however, block the possibility for designers to emerge more ideas from revising their sketches. The sketches of our other subjects in this experiment indicate that CAAD systems for novices should be easier and their representations should be less fixed since they tend to test and refine their ideas more.

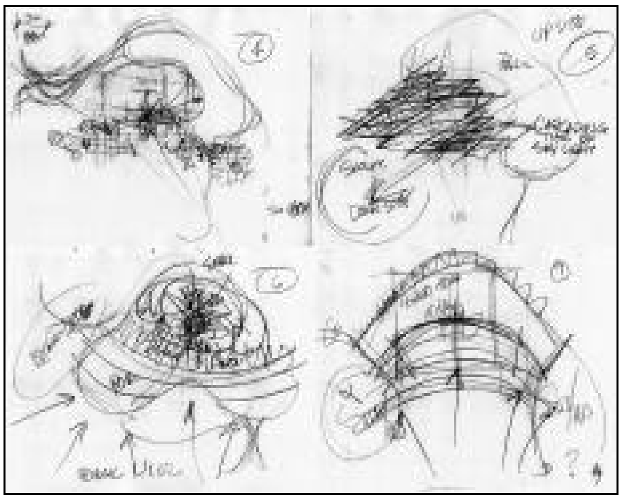

*Figure 1.* Numbers 4, 5, 6, and 7 of the expert's sketches

## 3.4 Multiple interpretations and relations between physical, perceptual, functional, and conceptual actions

This study confirmed that drawings or sketches have both perceptual and functional ambiguities and this may be why sketches play such important roles in the concept design process. In terms of perception and revision, the ambiguities provide opportunities to revise existing depictions and generate new spatial relationship from combinations as the source for aesthetic evaluations or form manipulation. Our data shows that during revisions designers regarded different depictions as one single element for functional manipulations although they were created individually at different times. Consequently, some depictions play several roles in different graphical and functional groups.

In terms of functional references, designers attached different functions to depictions without unchangeable fixations. They could be attached to overlapped areas and leave all the details for later consideration, or the functional references attached to depictions could evolve and change from time to time. There was no permanently fixed relation between depictions and functions in the concept design process.

This kind of vagueness and uncertainty really separates the conceptual design process from the rest of the design process, such as refinement and detail designs. During conceptual designing, designers play the essential role of confronting problems, generating ideas, and creating potential solutions, while during the rest of designing manufacturing and construction methods, building systems, and detailing occupy essential roles.

Corresponding to Norman's idea (Norman, 1998), the former part could be regarded as analogous to human-centre designing, and the latter part, to digital machine-centre designing. It is beneficial to apply CAAD systems to aid designers in generating the refinements and details of the design since it demands precision and accuracy for the mechanical process. CAAD systems successfully supported designers to realise structurally complex architecture that could not be built without the support of CAAD systems, such as the amazing works of Frank Gehry (Co and Forster, 1998).

What designers need to support conceptual designing are vague, imprecise systems to help them generate new ideas from their sketches. As a result, cognition-based CAAD means that at the early stage of designing such systems should support imprecision and indeterminism, but during the later stage it should be precise. Imprecision and indeterminism can be provided through a fluid representation schema that supports multiple views and multiple representations.

## 4. THREE MODES OF THE DESIGN PROCESS

After examining the design process from the viewpoints of speed and vagueness, we further examine the inter-relationships between physical, perceptual, functional, and conceptual actions. Based on the experimental data, we found that the design process may be viewed as a collection of modes, showing the directions of thinking process among four cognitive activities.

A sensor-driven process is one that is triggered by the designers' drawing and seeing. The reflective communication with the design media leads this process. A concept-driven process is one that is executed based on the designer's sub-goals or design strategies. The design media is used to realize ideas. A hybrid process is one in which perceptions and concepts interact with each other, and the design media is used both to present results and to stimulate thinking.

## 4.1 Sensor-driven mode

Given the four cognitive actions, sensor-driven modes are triggered by physical actions, including drawing and looking actions, toward the conceptual actions via perceptual and functional actions. In this mode, designers search for ideas or solutions through drawings and revising existing sketches. Drawings here are doodles and arbitrary lines because of no specific thought leading them. This mode benefits from the uncertainty and vagueness of the depictions, which produce more spaces to imagine and generate new spatial relations for functional references and reasoning. In our encoded data, 42 percent of the expert's segments and 29 percent of the novice's were pure sensor-driven, meaning no conceptual action was involved in that segment.

CAAD systems intending to support this mode should be able to support the vagueness of these drawings, the essential quality of this process. Designers can produce any lines and curves without interference from the interface. Such CAAD systems should provide the basic characteristics of using pens and papers, such as speed, extremely simple interface, but the sketches should be stored and be able to be manipulated later.

## 4.2 Concept-driven mode

In contrast, concept-driven modes are driven by conceptual actions toward the physical actions via perceptual and functional actions. In this mode, designers have more specific intentions or decisions, and they use sketches to externalise their thoughts, integrate them into the existing depicted design, and examine the feasibility through perceptions. Drawings here are more certain and clear, and most of the time they are modifications or additions of the existing depictions. However, our empirical data found no pure concept-driven process, meaning no physical actions involved.

CAAD systems intending to support this mode will have to have a simple verbal entry for graphical information. This is because in our analysis designers tend to handle simple issues in segments as well as through a consecutive series of segments and then solve larger issues. The process is similar to Simon's well-known proposal that designers break a complex goal into sub-goals and then integrate the sub-solutions to solve the original problem.

### 4.3 Hybrid mode

The discussion of sensor-driven and concept-driven processes in this study is supported by the conceptual model proposed by Galle (1999). Our results fit into the structure of designer's artefact-idea and design representation in which two actions are named: production and interpretation. Our findings verify its basic structure, but also propose a question for the structure. Our experimental data shows the actions are not always clearly distinguishable. The characteristics of the design process are sometimes like a mixture of both actions, a hybrid mode. The mode is driven by physical or conceptual actions toward physical or conceptual actions via perceptual and functional actions. The essential feature is the feedback from themselves, and drawings here have both features of those in the previous two modes.

The main characteristic found in all these modes is that these four cognitive actions are closely linked in the design process. There are very few instances that physical or conceptual actions exist alone in a segment. As a result, the vague drawings system and the simple-entry graphical information support systems should be integrated together, being coherent and compliant with different modes. Moreover, sketch-related physical actions appear in every segment, so this process should be regarded as a visual reasoning process, rather than pure information processing.

## 5. DISCUSSION AND CONCLUSIONS

In this study, we first explored the speed and vagueness of the conceptual designing process through our empirical data and analytical coding schemes. These two characteristics are probably the reasons why current CAAD systems failed to support conceptual designing and the possible impetus for a future CAAD system. Such a future CAAD system should be cognition-based, i.e. based on the cognitive behaviour of designers, the subjects CAAD systems intend to aid.

We discussed the design process in terms of four cognitive actions. Current CAAD systems benefit presentational drawing actions in a very detailed way, but offer no support for perceptual recognition and functional attachments. The connections between the sketches and these higher level cognitive functions are absent. Our empirical data, however, shows they are as important as physical actions and the four cognition actions are not separable in the design process. In the last ten years, little has been done in this aspect since Ullman, Wood, and Craig (1990) suggested that CAD was really only computer-aided “drafting”, and was not capable of supporting sketching in any meaningful way.

Finally, we discuss the design process and CAAD from three different design modes. From the viewpoint of sensor-driven processes, a CAAD system should provide quick access to represent ideas but the representation should not be fixed, to allow for the emergence of a variety of unexpected forms and spatial relationships. In terms of concept-driven processes, a knowledge base should support the design to accompany the sketches or representations since no pure information processing was found in the design process. Most importantly, in terms of hybrid processes, future CAAD systems should be integrated systems, assisting both higher and lower cognitive activities.

In the design community, Gross’s Electronic Cocktail Napkin project is a prototype diagramming environment aimed at conceptual designing process based on the similar ideas we proposed in this paper (Gross, 1996). In his CAAD environment, a pen-based interface supports the ambiguity and non-commitment required during conceptual designing, parsing and recognition systems analyse the sketches and their spatial relationships, constraint management routines keep the high-level relationship between diagrams. The purpose of that project is to support designers in the incremental formalization of the design process, from conceptual designing to schematic designing.

It is proposed, supported by our empirical data, that a cognition-based CAAD system would have the potential to benefit designers during conceptual designing more than current CAAD systems.

## 6. REFERENCES

Co, F.D. and K.W. Forster, 1998, *Frank O. Gehry: The Complete Works*. The Monacelli Press, Inc., New York, USA.

Ericsson, K.A. and H.A. Simon, 1993, *Protocol Analysis: Verbal Reports as Data*. MIT Press, Cambridge, MA.

Galle, P., 1999, "Design as intentional action: a conceptual analysis", *Design Studies*, 20 (1), p. 57-81.

Gero, J.S., (ed) 2000, *Artificial Intelligence in Design' 00*, Kluwer Academic Publishers, Dordrecht, Netherlands.

Goel, V., 1999, "Cognitive roles of ill-structured representations in preliminary design", in: J. S. Gero and B. Tversky (eds.) Visual and spacial reasoning in design, MIT, Cambridge, KCDCC, University of Sydney, Australia, p. 131-144.

Gross, M.D., 1996, "The electronic cocktail napkin - a computational environment for working with design diagrams", *Design Studies*, 17, p. 53-69.

McNeill, T., J.S. Gero and J. Warren, 1998, "Understanding conceptual electronic design using protocol analysis", *Research in Engineering Design* 10, p. 129-140.

Norman, D.A., 1998, *The Invisible Computer*. MIT Press, London, England.

Schön, D.A. and G. Wiggins, 1992, "Kind of seeing and their functions in designing", *Design Studies*, 13 (2), p. 135-156.

Suwa, M., J.S. Gero and T. Purcell, 2000, "Unexpected discoveries and S-invention of design requirements: important vehicles for a design process", *Design Studies*, 21, p. 539-567.

Suwa, M. and B. Tversky, 1997, "What do architects and students percive in their design sketches? A protocol analysis", *Design Studies*, 18, p. 385-403.

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

Ullman, D.G., S. Wood and D. Craig, 1990, "The importance of drawing in the mechanical design process", *Computers and Graphics*, 14 (2), p. 263-274.

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