Computational Sketch Analyser (CSA): Extending the Boundaries of Knowledge in CAAD

Jeanette McFadzean

This paper focuses on the cognitive problem-solving strategies of professional architectural designers and their use of external representations for the production of creative ideas. Using a new form of protocol analysis (Computational Sketch Analysis), the research has analysed five architects’ verbal descriptions of their cognitive reasoning strategies during conceptual designing. It compares these descriptions to a computational analysis of the architects’ sketches and sketching behaviour. The paper describes how the current research is establishing a comprehensive understanding of the mapping between conceptualisation, cognition, drawing, and complex problem solving. The paper proposes a new direction for Computer Aided Architectural Design tools (CAAD). It suggests that in order to extend the boundaries of knowledge in CAAD an understanding of the complex nature of architectural conceptual problem-solving needs to be incorporated into and supported by future conceptual design tools.

Keywords: Computational Sketch Analysis, Conceptual Design.

Introduction

Computer Aided Design (CAD) was first developed in the 1960’s and has evolved to become an intricate part of architectural practice. However, one of the most time consuming phases of the design process and the one that makes the greatest demands on the designer, the conceptual design process, is still not fully supported by current computational tools. Goel (1995) argued that sketching, in this early phase of design, plays a critical role in the inception and future development of creative ideas. Designers at the conceptual stage, rely on sketching as a form of visual reasoning for the exploration of creative ideas. Through interaction with the sketch designers evolve the design problem space, so that it moves from an ill-defined set of constraints to the identification and resolution of creative ideas.
cognitive interaction with their external representations.

**Cognitive processes in Conceptual Design**

Conceptual design is characteristically different from other phases in the design process. It is characterised by divergent thinking, as designers need to manipulate the design problem space to obtain a better understanding of the nature of the design problem. Like other creative domains, architectural conceptual design involves: the extraction of information from memory (fact-finding), reasoning and exploration (idea-finding) and the evaluation of attributes and resolution of specific problems (solution-finding and acceptance-finding). These cognitive skills are applied to the design problem space at many different levels of abstraction. The design problem may be characterised by ambiguity, or aspects of the design may be resolved whilst other parts may be left open and therefore unresolved. Thus the designer designs under ill-defined conditions and with uncertainty (Cross, 1989; McFadzean et al. 1999).

Certain cognitive skills seem to underlie this creative behaviour: fluency, flexibility, visualisation, imagination, expressiveness and openness (van Gundy 1987). Sketching is a key component in visualisation and expressiveness and in the architects’ ability to resolve a design problem space.

Mental visualisation of patterns is reported to produce creative insights in problem solving across most domains of knowledge. In the initial stages of conceptual design the designer must consider numerous constraints. When the problem space is greater than that sustainable by short-term memory, sketching becomes a tool, allowing the user a feedback mechanism for information storage and retrieval. The use of sketching allows greater flexibility when manipulating the constraints of the design problem space, thus cognitive activities such as attention, focusing, retrieving emergent properties, association, synthesis and analysis seem to be used in more productive ways (Fink, 1996; van Sommers 1984).

**Protocol Analysis**

Although sketching is widely acknowledged as an important part of the process of designing, research has only recently been carried out into the role of external representations and how they aid designers’ cognitive processing of design information.

Protocol analysis is a research method which relies on verbal accounts given by subjects describing their own cognitive activities whilst participating in a task. It is a method that has been used successfully to analyse aspects of design activity (Cross et al.) and this has led to a better understanding of the needs of designers. However, the method has only recently been used to examine the use of sketches during conceptual designing (Do, 1996; Suwa et al. 1998).

This paper builds on recent findings from studies of sketching and proposes that by bringing together this empirical evidence with studies from design science (Cross et al. 1996) and cognitive psychology (Fink et al. 1988, Fink et al. 1996, Karniloff-Smith, 1995). CAAD tools can be extended beyond their present capabilities.

**Computational Sketch Analysis (CSA)**

The current research has developed a new computational form of protocol analysis, ‘Computational Sketch Analysis’ (CSA), for the assessment of architects’ conceptual sketching during complex problem solving. CSA has been developed, to record and elicit data at the micro level of sketching (McFadzean, 1998). It consists of two pieces of software: a Data Collector and a Sketch Analyser. The Data Collector captures and timestamps all graphical data from the design session. The Sketch Analyser serves two functions.

- It acts as a record of the sketching activity
that can be replayed to the designer retrospectively, for comments and analysis.

McFadzean, Cross and Johnson (1999) used this method to capture architects’ verbal descriptions of their cognitive reasoning strategies during conceptual designing.

- It is an analytical tool that dynamically builds a computational profile about the architects’ design sessions.

The lowest processing level of the Sketch Analyser captures all the graphical notation of the visual representations generated during a design session. The next level uses this information to dynamically assess attributes of the architects’ conceptual designing. It collates information on sketching behaviour. For example, it examines the cognitive chunking of the sketching activity for each architectural designer and produces 3D maps of this data. At a higher level ‘The Sketch Analyser’ extracts information about the sketches such as; the lines, shapes and structures. The process is one that uses a representational schema derived from the results of observations in an early study (McFadzean, 1998) together with a graphical classification-encoding schema based on the salient principles that govern drawing (van Gundy, 1987; Ullman et al. 1999; Jenkinson 1990) to determine how sketches are constructed. Examples of some salient graphical principles in the taxonomy are presented in Table 1.

This new method of collecting data allows a rigorous and consistent analysis of the graphical sketch notation used by architectural designers. CSA is a more appropriate method of data collection and

<table>
<thead>
<tr>
<th>Graphical Principles</th>
<th>Types</th>
<th>Intentions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marks</td>
<td>Non-iconic marks</td>
<td>Dealing with abstract properties of the sketch - Constraints, Questions, Functional Issues</td>
</tr>
<tr>
<td></td>
<td>Iconic marks</td>
<td>Used for recalling information used previously</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copying a previously designed part over for detail</td>
</tr>
<tr>
<td>Graphical constraints</td>
<td>Starting position</td>
<td>Readability</td>
</tr>
<tr>
<td></td>
<td>Preferred stroke direction</td>
<td>Construct representation based on Gestalt theory</td>
</tr>
<tr>
<td></td>
<td>Resisting anticipated embedding</td>
<td>Simplify structural properties</td>
</tr>
<tr>
<td></td>
<td>Accretion</td>
<td></td>
</tr>
<tr>
<td>Overdrawing</td>
<td>3 movements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Return overdraw</td>
<td>to extend the line</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(After a pause) recalling previous thoughts</td>
</tr>
<tr>
<td></td>
<td>Overdrawing of faint lines</td>
<td>Global creation of drawing</td>
</tr>
<tr>
<td>Drawing faintly</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible used to draw to record</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deliberate decision to use faint lines as a construction device</td>
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<tr>
<td></td>
<td></td>
<td>Suggests a degree of caution</td>
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<tr>
<td>Tentativeness</td>
<td>Drawing faintly</td>
<td>As drawing faintly</td>
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<tr>
<td></td>
<td></td>
<td>Indecision</td>
</tr>
<tr>
<td>Non-mark, marking,</td>
<td>Hovering</td>
<td>Indecision</td>
</tr>
<tr>
<td>movements</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moving towards and then away from the drawing area.</td>
<td>What to draw?</td>
</tr>
<tr>
<td></td>
<td>Rehearsing an intended mark</td>
<td>Sizing / measuring, thinking about structural properties</td>
</tr>
</tbody>
</table>

*Table 1 (right). Example of salient graphical principles*
analysis for the study of sketching activity in the discipline of design, because a stream of time-stamped, stroke co-ordinate data allows graphical events to be abstracted automatically.

**CSA for the analysis of cognitive reasoning strategies**

In order to understand how the construction of external representations aid in the process of resolving architectural conceptual design problems, research has been carried out by McFadzean, Cross and Johnson (1999a,b) using CSA. It has examined professional architectural designers’ cognitive processing of design information and their sketching activity.

**Experiment**

Five CSA experiments were undertaken using architects with between 2 and 20 years professional experience. The experiments were identical, lasting between forty-five minutes to one and a half-hours. The designers undertook two tasks: a design task and a retrospective report task. The design task asked the participants to design a “smokers' lodge” for a University campus. Participants were given a design brief, after which they were taken to a site that could potentially house the lodge. On returning they were asked to produce conceptual designs, on an A3 graphics tablet using lead pencil or ink pen on paper. The task was recorded using the Computational Data Collector. Following the design task, the participants watched a replay of their sketching activity, using the Sketch Analyser. They were asked to report on what they were thinking when they were generating each pencil stroke.

**Coding Schema**

The research has developed a classification-encoding schema suitable for examining designers’ cognitive processes (McFadzean, Cross and Johnson, 1999b,c). The verbal descriptions were segmented into small units. Segmentation of the units occurred when the participant paused for longer than two seconds, or when the experimenter interjected.

**Taxonomy of Design events**

Each segment of the designers' verbal description was coded into different modes of cogitation, which were called Design Events [A]. There were nine Design Events: External Memory Aid, Emergence, Constraints, Abstraction of the Design Problem, Reasoning/Exploration, Problem Defining/Resolving, Reflection, Construction of External Representations, External Visualisation Problems. The encoded Design Events were extrapolated from the transcripts and plotted as instances over time (McFadzean, Cross and Johnson, 1999a).

The taxonomy of Design Events has allowed observations and inferences regarding the patterns of design reasoning strategies supported by sketching. A statistical analysis of the data highlighted a cognitive network of interactions appertaining to the processing of design information for all the architects (McFadzean, Cross and Johnson, 1999a). A study of this network has indicated that different architectural designers’ use key cognitive processes time and time again in similar ways. This infers that expert designers share conventions in their use of sketching.

Two propositions can be drawn from these results; either professional architects have become apt at using sketching to facilitate specific cognitive states of the design, or the cognitive states enable visualisation that is partially externalised by sketching. Both assumptions infer that sketches may encapsulate cognitive chunks of design information. Thus the analysis of sketching can provide a means by which to analysis and aid cognitive processing in conceptual designing.

**The analysis of sketching activity**

A detailed study of drawing activity carried out by Van Sommers (1984) has contributed towards our comprehension of the limitations and advantages of external representations. However, it was confined
to the analysis of general drawing tasks carried out by non-designers. Relatively few studies have analysed the drawing activity of expert designers during complex problem-solving. Increasingly research regarding the drawing activity of individuals is focusing on novice and expert designers, as their use of external representations is often fundamental to their ability to design creatively. Researchers have begun to realise that a relationship exists between the low-level mark-making activity and the designers’ accuracy of representation, intentions of representation, visualisation and cognitive processing of design information.

The speed of the designers’ drawing activity can be associated with different stages of the design process, i.e. conceptual design, embodiment phase and detail design (Ullman et al. 1990). Jenkins (1990) has researched this line of study, by observing architectural designers’ use of different types of mark-making activity. He proposed that a relationship existed between the types of mark-making and the intentions of designers. The ‘cognitive network of interactions’ (McFadzean, Cross and Johnson, 1999a), discussed in the previous section, indicates that this is the case. When the designers’ intentions are to reason and explore the dimensions and structural properties of the design problem, they ‘redraw’ previously drawn elements and ‘draw over’ existing marks. This stimulates an interactive relationship between the constraints of the design and the mark-making activity. When this interaction takes place expert designers report that new shapes, concepts or visual memories emerge out of the visual inspection of the external representations.

**CSA for the analysis of sketching activity**


CSA uses computational techniques to extrapolate measurable differences in the participants’ sketching activity. The Drawing Analyser has been developed to automatically encode the time-stamped data into different types of drawing acts. At the lowest level of detailed analysis, the research investigates how designers sketch, specifically analysing the physical details of mark-making. Attributes of mark-making that are extracted include orientation, speed, pressure, length and time, and distinctions are made computationally between aspects such as text and drawing. We refer to this as the ‘Computational Representation of Sketching Behaviour’. At the higher level of detailed analysis, the research has investigated what designers sketch, i.e. lines, open or closed shapes. We refer to this as the ‘Computational Representation of Sketches’.

**Methodology for the computational representation of sketching behaviour**

The research has implemented the computational analysis of:

1. The segmentation of graphical data into cognitive chunks of information.
2. The externalisation of the cognitive chunks; in the form of ‘3D behavioural maps’.
3. The mapping of the cognitive chunks to the designers’ physical actions, in terms of pressure and speed of the mark-making activity.
4. The mapping of the designers’ externalisations to the computational representations of the physical actions.

**Methodology for the computational representation of sketches**

CSA uses a representational schema [13]. At the lowest processing level are the types of points(x) in the sketch. The next level extracts the lines and trajectory information, to define sets of graphical
notation, such as threaded links (corners) arcs, and circles. These lines then form sets of ‘primitives’ and ‘forms’ that can be grouped together to produce sets of ‘representations’. Sets of representations then form the architects sketch.

**Mapping external representations of cognitive thoughts to extend the boundaries of CAD**

The research is in the process of building a taxonomy of Graphical Events that builds a profile of expert architects sketching behaviour. This detailed analysis of how representations are constructed will help to build a formal description of experts’ use of graphical notation in architectural conceptual designing.

The research is analysing the associations between the sketching activity and the Design Events. This paper proposes that differences in sketching activity may be mapped to the cognitive processing of design information, i.e. the taxonomy of the Graphical Events may be mapped to the taxonomy of Design Events. It is expected these associative mappings will allow the extraction of denotational sub-systems that relate to the expert designers’ mode of problem solving with the syntactic structure of external representations. The objective is to understand how graphical notation is utilised as a problem resolution device and how it is used to define architectural design problem spaces.

**Results**

The results of the research have shown that denotational sub-systems can be extracted from the participants design sessions. Figure 1 shows some examples of the spatial frequency between the different types of mark-making activity and their associated cognitive reasoning strategies.

**Further Research**

Current research is investigating how the expert architectural designer used the graphical salient principals throughout their design sessions. It is proposed that an insight into experts sketching behaviour and the understanding of the interaction of the denotational sub-systems will provide means by which to implement effective computational support tools, for novice and expert designers.
Conclusion

Support for the conceptual cognitive needs of architectural designers forms an important future direction of CAAD research. This paper contributes towards design education by gaining an insight into architectural design expertise. The problem of how architectural designers’ formalise their design thoughts, is an issue that needs to be considered when building computational support tools that aid conceptual design.

The paper has addressed a significant aspect of experts visual thinking and reasoning in architectural design problem solving - the relationship between what is drawn and the cognitive processes that are associated with the sketch. This paper has highlighted the link between sketching activity and cognitive thought in expert architects. It suggests that a future direction for CAAD research is the understanding of the mapping between designers’ cognitive thoughts and their external representations.

A way has been found for directly inputting what is drawn, into a computer and software has been developed that analyses the drawings. This paper proposes that Computational Sketch Analysis is necessary and fundamental to the advancement of current architectural design tools [14], because if sketching provides a quantifiable way of identifying architectural designers’ activation of cognitive skills, CAAD could potentially utilise sketching to support the cognitive processes involved in conceptual designing.

In order for computational tools to correlate sketching activity with the cognitive processing of design information there must be formal descriptive methods for the classification of different types of activity within both the graphical and the cognitive systems. The classification-encoding schemas for the systems must provide rigorous and quantifiable means of measuring different data types. This paper has suggested that CSA can be extended to construct a high level cognitive analysis, so that the designers’ evolution of the conceptual design problem space can be mapped.

References


Cross, N. Engineering Design Methods (John Wiley & Sons Ltd. Chichester, 1989).


Notes
[A] Design Events are defined here to be processes that manipulate chunks of information, representing important incidents that occur during the process of conceptual designing. Design Events are not considered to be mutually exclusive thus a chunk of information may have more than one Design Event attached to it.
[B] Graphical Events are defined as the processes which manipulate ‘chunks’ of notation that emerge out of a lower-level data set of the graphical notation of sketching.

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