BEYOND SKETCHING: VISUAL REASONING THROUGH RE-REPRESENTATION IN COGNITIVE DESIGN MEDIA

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Abstract. Our research approach which is termed *Cognitive Design Media (CDM)* demonstrates how the cognitive phenomena of design can be supported in computerized environments. Our current work on the 'sketch' project is introduced presented and illustrated. Sketching in design is considered to be one of the significant cognitive phenomena which supports exploration through re-representation in design. Until now, only the medium of hand drawing and sketching has been considered to support these processes. Rather than automating the traditional hand-made sketch, or interpreting sketches in a computer system, we are attempting to employ the computer to support one of the cognitive mechanism of re-representation which underlie the sketch activity.

1. Introduction: Computational Support for Visual Reasoning

1.1 Cognitive Design Media

Cognitive design research has provided deep insights into various aspects of design. Through this research it has become obvious that design shares many unique characteristics with respect to subjects such as creativity, visual reasoning, analogies and metaphors, which are common to all fields of design. We term our research paradigm, *Cognitive Design Media* (CDM). CDM are defined as media which support such cognitive phenomena of design in computerized environments. Cognitive Design Media are computational environments which do not explicitly model human reasoning in design, but rather implicitly support the cognitive capabilities of the designer. That is, based on cognitive models of design we can computationally support the cognitive properties of design tasks in interaction with the human designer.

We have employed the term Cognition and Computation to emphasize the cognitive nature of the design phenomena which we are attempting to define, formulate, model, and implement. In a recent special issue of Design

Studies devoted to Design Cognition and Computation (Oxman, 1996) we have demonstrated the significance of this research orientation as an integrated research approach. The distinguishing characteristic of cognitively responsive systems is that they exploit *computational technologies* which suit the interaction between *cognitive models* and *design domain content.*

These three elements of cognitive design media include cognitive models such as visual reasoning which include the cognitive aspects of designing; design domain content includes the particular knowledge of the domain and its related task knowledge; technological media provide the computational environment. It is the intersection between cognitive models, technologies and domain knowledge which is the hallmark of research and development in the field.

1.2 COGNITIVE MODELS IN DESIGN

Cognitive models of design are formulated on the basis of both empirical work, and theoretical work. The work employs cognitive models based upon cognitive theories and, whenever possible, on complementary empirical work. With respect to research methodology, a symbiotic relationship is developed between empirical and experimental research in design thinking resulting in knowledge which can be subsequently recycled into the development of design systems and tools. The cognitive knowledge gained, empirically or experimentally, is an important pre-requisite to the development of cognitive-based tools which can support design. Thus the cycle of research-oriented work in *cognition and computation* which has helped to formulate our knowledge of design thinking is now becoming the foundation and resource for what is a powerful paradigm: computational design environments which are responsive to, and can enhance, the cognitive properties of design.

1.3 RE-REPRESENTATION IN COGNITIVE DESIGN MEDIA

The cognitive phenomena of visual reasoning (Arnheim, 1969) in design has introduced a *cognitive orientation to visual reasoning as a foundation of design thinking.* Visual reasoning has been recognized as a reflective process on the problem in the medium of conceptual drawings, or sketching. The basic characteristics of sketching enhance the dialectical nature of design as a reflective process of both visual and verbal thinking in design. The complexity and significance of this cognitive phenomena in design influences the way in which the designer develops visual representations which support the exploration of new design ideas.

Sketching in design is considered to be one of the significant cognitive phenomena in visual reasoning which supports exploration and creativity in design. Several researchers have emphasized the role of drawings, sketches and diagrams in visual reasoning in design exploration. Schon employed the term "reflection in action" is his model for the description of a dialectical duality in

cognitive design processes employing both modes of thinking, visual and conceptual (Schon and Wiggins, 1992). Lawson describes this in a similar way as "having a conversation with the drawings" (Lawson, 1980). Suwa and Tversky (Suwa and Tversky, 1996) in their study of design sketching presented the relation between 'concepts' and the resultant act of sketching. The primacy of these cognitive characteristic demands a cognitive model of design thinking which reflects both the duality of modes (visual/verbal) and their dialectical interaction in design thinking.

Exploration in design has been recognized as a process of perception, conception and presentation (Simon, 1992). This sequential serial process of presentation and re-representation results in a series of transformations on externalized presentations. According to Simon, drawings are employed for the externalization and 'holding' of these representations. Design cognition is characterized by a sequential clarification through supported by perceptual conceptual and interpretation processes. The properties of the sketch, such as ambiguity make it a suitable medium for re-interpretation.

1.4 A COMPUTATIONAL SUPPORT FOR RE-REPRESENTATION IN VISUAL REASONING

Until now, only the medium of traditional hand drawing in sketching has been considered to support these cognitive processes. Recently, approaches in computer aided design which are relevant to these cognitive phenomena have been developed. The Electronic Cocktail Napkin (Gross 1996, Gross and Do, 1996) was a prototype constructed on top of a freehand drawing program and explored how computer-based sketching programs can provide an enhanced environment for design. In their work they have attempted to show how they might support certain cognitive processes in design such as the recognition of emergent shapes. However, even when such computer programs exhaust all possible emergent shapes, the designer must still choose a preference (Soufi and Edmonds, 1995). Another approach employs computational models of visual reasoning as a way to provide constructs for re-interpretation via re-representation (Damski and Gero, 1994). According to this approach the two relevant issues are: how to re-represent and how to re-interpret.

In our work on visual reasoning we also deal with the problems of re-representation and re-interpretation in sketch design. However, rather than automating sketch interpretation, or constructing computational models of visual reasoning, we attempt to employ the computer to support the *cognitive mechanisms which underlie the sketch activity.*

In this paper, we report on work in which media environments are developed which support *cognitive mechanisms* in design thinking. In the next section we introduce and present the cognitive concept of re-representation. In the following section we discuss the role of generic schema in design as a underlying cognitive basis for re-representation. Following this, we

demonstrate the role of typology as domain content which can be integrated within generic schema and which provide supportive knowledge for different classes of design problem. So a cognitive model of representation requires relevant generic schema and typological knowledge suitable to the problem class. Finally we present our initial ideas and work on computational support for re-representation in design

2. Re-Representation as a theoretical foundation for visual reasoning

Sketch drawings are assumed to act as a cognitive medium for the externalization of design representations. In a typical process of design development, sketch drawings are employed for the externalization of design representations in order to construct new ones from exiting ones. The cognitive ability to construct a new representation is termed *re-representation*.

What is re-representation and what is its importance? According to Simon, drawings are employed for the externalization and 'holding' of internal representations in a perception-conception cycle. This sequential serial process of presentation and re-representation results in a series of transformations on the externalized representations. It is these transactions with the external representation, usually in the process of sketching, which are considered to illuminate the visual-mental processes of designers (Oxman, R.M.,1995). In interacting with visual representations, the process may also include the explication through processes of re-representation of internal representations. According to this view, re-representation, is the external manifestation of the process in which design representations are transformed and is a medium of design exploration.

We have presented a model of visual reasoning in design which is based on a *cognitive mechanism of re-representation*. How does re-representaion operate, and what theoretical framework enables us to model the process of re-representation? The theory of re-representation is a cognitive approach which explains creativity as an act of "conceptual exploration through re-representation" (Karmillof-Smith, 1993). Re-representation theory explains the way in which human beings explore new modifications through the externalization of knowledge structures in representations.

2.2. RE-REPRESENTATION AS A COGNITIVE MECHANISM IN VISUAL REASONING

Re-representation is an important phenomena which has become a theoretical basis for work in areas such as creativity and adaptation in case-based creative design (Oxman, 1994). In the theory of case-based design, a specific solution in the form of a design case, or part of a case, is selected and, through adaptation, transformed into a new design. Adaptation processes can be defined as successive modifications through a series of re-representations which are

executed upon the design case. Through empirical research the classes of re-representations can be observed as well as the way in which designers interact, modify and change them. We have referred to this process as *design re-representation* (Oxman, 1996;1997), exploiting the term which has been applied to the cognitive phenomenon as well as to the cognitive capabilities which make these complex processes possible.

Our empirical studies (Oxman, 1997) have demonstrated the role of multiple representations in visual reasoning in design drawings. In our empirical work of these studies of re-representation designers were asked to analyze and explicate the various underlying representations behind a design. They were asked to modify and change the design in a computer environment in order to fit external requirements. In the computer environment, which served as a recording medium, the content of the representations were analyzed in an explicated form. The designers, by distinguishing the content of each one of the multiple representations, could then make their modifications directly upon the explicit representations. We were thus able to determine what knowledge was implicit in the process of re-representation. What classes of knowledge actually underlie the ability to modify a representation.

Our empirical research on re-representation and multiple representations has also provided evidence for the existence of these cognitive abilities of the designer to perceive and to evoke generic types during the process of design, and to and discover emergent design classes. Both of these phenomena the discovery of the generic in the specific, and the ability to read emergent form in the graphical representation are two classic elements of visual reasoning which can be explained by re-representation theory. A key-stone of this theoretical explanation is that the recognition of generic content is an intermittent cognitive phenomenon even when working with specified images.

3. Re-Representation, Generic Schema and Design Typologies

A significant aspect of re-representation is the underlying role of generic reasoning in re-representation (Karmilloff, 1993). The process of re-representation suggested by Karmilloff-Smith is relevant to design exploration, since it involves conscious cognitive construction and exploration of the *structures of schema*. Prior knowledge enables the designer to evoke generic representations, or to extract the schema from specific images.

Generic representations may be considered one kind of such knowledge structures. The accessing of a generic schema of the representation is one of the cognitive phenomena which makes its re-representation possible. Thus generic knowledge is one form of knowledge which is necessary to re-representation.

Our research has substantiated that the structuring and restructuring of shapes through multiple re-representation evidence the cognitive capability of the designer to evoke such knowledge structures. Furthermore, recognizing

design classes during a re-representation process may evoke their associated generic representations and the unique operations associated with the particularization of the generic representation.

3.4 TYPOLOGY: DOMAIN CONTENT IN GENERIC SCHEMA

Within the context of generic processes in re-representation, we employ the term typology as design domain knowledge of classes of design problem types. One of the most significant schematic representations which designers employ in the graphical development of design representations is knowledge of the type (Oxman and Oxman, 1992). Typologies may have generic representations which are specific to the typological class. Thus each typology implies the existence of a schema of generic representations. Typological knowledge is characterized by a set of generic representations which are associated with specific problem types, and the knowledge of the variables of the type is organized in a hierarchical order of which the highest level is that of the schematically represented class description. During design exploration within typological design, designers generally interact with the graphic representation employing the sketch drawing technique as a medium for visual reasoning within and between the schema of types. Our research in visual reasoning has indicated that re-representation requires the ability to evoke both schema and type class variables in order to support re-representation (Oxman, 1996, 1997).For example, typological knowledge of classes of chair design help the designer to evoke generic schema which support graphic modifications of the schema and its variants.

Furthermore, each typological schema can be re-structured, or componentized in a different ways, thus creating sub-schema, or even new types. The designer can decide how he wishes to 'break', or re-structure the representation. For example, in the case of chair design, the typology of the chair can be represented as a holistic component or by various combinations of sub-components. Secondly, within each particular element of structure parametric modification is also possible as a means to differentiate the image. For example, the following figures illustrate two analyses of possible representations which are derived from the same typologies. In figure 1 the typology, is resulted in the ladderback chair by C.R.Mackintosh. In figure 2, the same typology has resulted in a bench-based chair by Maichele de Luchi. .

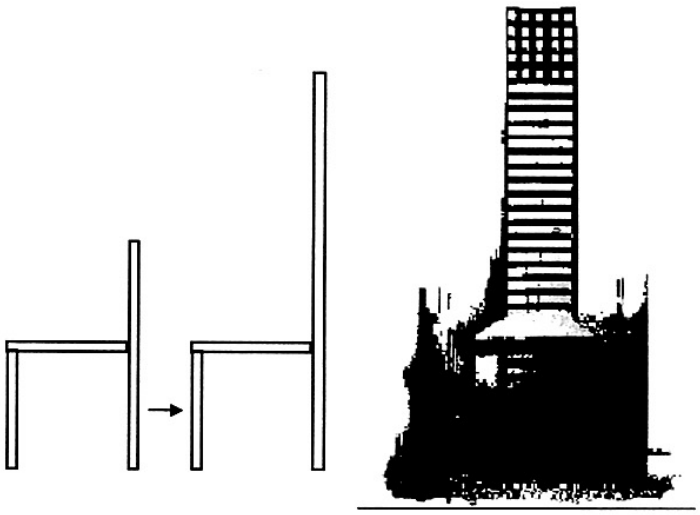

Figure 1. Re-representation for a chair design: The 'Ladderback chair by C.R.Mackintosh' associated with generic representation of 'tall proportion' (analysis done by Zvi Zyit and Aviram Kuri)

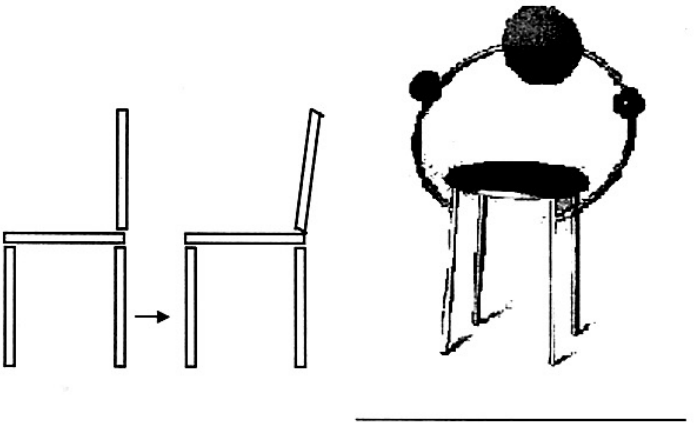

Figure 2. Re-representation for a chair design: The 'First chair by Maichele de Lucchi' associated with generic representation of a 'benched-based chair' (analysis done by Zvi Zayit and Aviram Kuri)

We are attempting to develop a CDM which will support the inter-relationship between generic schema and typological knowledge. In the following section, we describe this system.

4. A Computational Support for Re-representation in Design

The CDM attempts to produce a computational medium to support the cognitive mechanism of re-representation in visual reasoning. In our approach, the computational environment behaves as an interactive design medium which is strongly related to the cognitive capabilities of the designer. Re-representation is supported by providing an interactive interface which assists in the construction of new representational structures which can be derived from existing ones. The representational system operates through the maintenance of generic schema and typological knowledge while enabling modifications within the type. The typological generics act within the background while the designer interacts with the representation dynamically employing the mouse in order to achieve transformations. Once the limits of a typological schema have been reached by the designer, he is free to transform the typological schema and then explore variations within the new typological framework.

Our system currently supports two levels of dynamic variability of the representation. First, each representation can be re-structured, or componentized in a different ways. The designer can decide how he wishes to 'break', or re-structure the schematic typological representation, e.g. as seen as a structuring of the elements of the chair frame. The typology of the chair can be represented as a holistic component or by various combinations of sub-components. Secondly, within each particular element of structure parametric modification is also possible as a means to differentiate the image. Thus the designer can work in the current system at the two levels of the type and its variants, or can modify the type classification. Ultimately we hope to be able to move automatically through type classes as the designer makes specific modifications in the representation.

While we currently work directly on the visual image itself, we are developing a dual representational interface which will enable the designer to work directly on the modification of the generic type though modification of the structure of the code itself. Re-representational possibilities can be provided in such a system through an interface which provide changes of external representation through modifications of the internal code structure. We believe that such a combination interface, exploiting both physical and diagrammatic representations may provide a new form of graphical interface to support the exploration, explication and development of generic schema by changing the internal structure of the code of the data-base of the representation.

In our current example, we employ the VRML code of a graphical model which is presented in three-dimensions. Figure 3. illustrates an example from our work in the re-representational support of chair design. The representation employs a rather traditional structure of a chair: a seat, support, and legs. Each representation is provided with 'modification buttons'. In this example, clicking the various buttons, results in size modifications of components. When

the chair is structured in a different way, the process of parametrisation could result in different images of the chair design. In the present case study underlying chair schema are made explicit through the componentizing facility, which can then be modified by size.

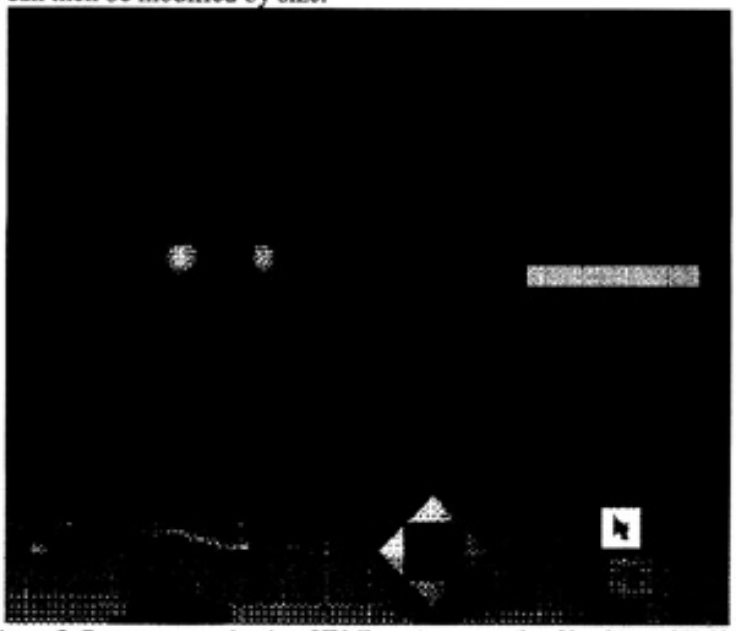

Figure 3. Re-representation in a VRML environment (by Shaphir and Yukla)

5. Conclusions

Underlying the term Cognitive Design Media are a set of theoretical assumptions. First of all, through the integration of cognition and computation we can gain new a theoretical basis and understanding of how computational design tools should be developed and employed by the human designer. With respect to research methodology, both empirical research and experimental research in design should be applied in computational design research. Computational environments should be responsive to and enhance the cognitive properties of the designer.

CDM was defined as a medium which *supports the cognitive nature of design in computational environments which do not explicitly model human reasoning in design, but rather implicitly support the cognitive capabilities of the designer*. That is, we can computationally *support the cognitive properties of design tasks in interaction with the human designer*.

The potential of this approach was illustrated by work in the area of conceptual design. We demonstrated through an example of chair design how design can be supported in interactive computational environments which

integrate the cognitive capabilities of generic thinking with the typological classes of knowledge in the domain of chair design. Within such a design domain, the system supports "sketching" and modifications within and between typological classes of solution types. On the basis of our current findings we believe that the idea of computational media based on cognitive properties of the designer and providing cognitively responsive interactive design environments provide a an important paradigm for design aid systems.

Acknowledgments

I wish acknowledge my students who participated actively in these experiments for the implementation: Oren Shafir, Michal Yukla; for the analysis: Zvi Ayit, and Aviram Kuri. The theoretical and empirical research and the implementation was supported of the Fund for the Encouragement of Research of the Technion. Part of the research was funded by a DFG grant.

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