Design by re-representation: a model of visual reasoning in design

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The conception of design as a sequential process of description and re-description in the development of designs is presented. Re-representational theory (RRH) is introduced and the cognitive mechanisms which enable re-representation in design are explicated. A theory of re-representation and multiple representations in design is proposed. The concept of adaptation developed in CBR is exploited to formalize transformations in the re-representation process. An empirical research was constructed to study the cognitive abilities which underlie the creative phenomena of re-representation in design adaptation. On the basis of the findings of the experiment, a model of design re-representation is developed and presented. The main concepts of the model, multiple representation and re-representation, are shown to provide a powerful basis for the understanding of creative behavior in design. © 1997 Elsevier Science Ltd.

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The design sketch can be considered as the basis of a visual and mental transaction between the designer and the representation, which evokes a discrete graphical response. According to Schön, the designer is engaged in 'graphical conversation with the design'[1] or according to Lawson, 'the designer has a conversation with the drawing'[2]. It is these transactions with the external representation which illuminate the visual–mental processes of designers. Where graphic media such as design sketches are the medium whereby the design is evolved, design moves are 'a series of actions' of the designer which result in transformations of a representation[2,3]. The term 'move' is frequently employed in contemporary design research to describe the discrete increments of change in the evolution of a design.

This elucidates one of the distinctive characteristics of the graphical design process, particularly the process of conceptual design, namely, its develop-

1 **Schön, D A** *The Reflective Practitioner: How Professionals Think in Action* Basic Books, New York (1983)
2 **Lawson, B** *How Designers Think* The Architectural Press, London (1980)
3 **Akin, O** *Psychology of Architectural Design* Pion, London (1986)

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ment through a sequence of progressive stages over time. The sequence of sketches can act as a record of reasoning processes which can be inferred from a *transition of states* from one representation to a subsequent representation.

Typical processes can be interpreted and categorized as classes and types of modification of the representation[4]. According to Arnheim[5], cognitive operations in perception in design include distinguishing structural relationships of the images in the design representation. This includes the interpretation and conception of such structures of relationships (prototypes). Spatial gestalt and the structural qualities in configurations are extremely significant in conceptual design. The structuring and restructuring of shapes which may be observable in sequences of sketch design representations evidence the cognitive abilities of the designer such as the ability to evoke prototypes.

The way creative designers fit and adapt graphical representations through drawing and redrawing is one of the least understood phenomena in design. Despite current work in understanding graphical reasoning in design, the way perceptual and conceptual mechanisms operate in design drawing are still unformulated. The way knowledge is employed and sequential clarification and conceptual enrichment are supported in design requires study, understanding and formalization. These are among the objectives of our work.

Formalizing the procedural aspects of design moves may contribute to our ability to model visual reasoning in design. This description–re-description process is one way in which designers cognitively exploit graphical representations[4] and is, therefore, relevant to the modeling of design. Sequential modification in design drawing is a medium through which design processes operate and are made manifest.

1 *Towards a* re-representation model *of visual reasoning in design drawings*

In this paper, we propose a model of the cognitive mechanisms and abilities which underlie and enable sequential states of graphical re-representation in design. With reference to certain relevant psychological theories cited below, we refer to this model as a *re-representational model of design reasoning*. The modeling is founded upon an empirical study of designers' behavior in the graphical adaptation of a design solution. The objective of the experiment was to study the way designers manipulate graphical symbols in design drawings, and to identify the knowledge and cognitive capability required to enable re-description in design.

4 **Oxman, R M** 'The reflective eye: visual reasoning in design' in **A Koutamanis, H Timmerman and I Vermeulen** (eds) *Visual data bases in architecture* Averbury, Aldershot, U.K. (1995) pp 89–112.
5 **Arnheim, R** *Visual Thinking* University of California Press, Berkeley and Los Angeles (1969)

We have modeled the knowledge employed in visual reasoning in the interaction of graphic design presentation. It is these transactions in a graphical medium which we attempt to study, to model and to formalize. As we demonstrate through psychological studies, this level of knowledge underlies the cognitive ability for structuring, or generalization, of the representation. We have proposed a re-representational model which attempts to identify and formalize the level of knowledge which is required for making transformations of re-representation in the interaction with the graphical medium. As a result, we identify and characterize the transformational processes involved in increments of state transaction. Furthermore, we explicate the explicit sets of knowledge structures which enable them to occur.

This experiment throws light on the differences in the cognitive ability of individual designers. It also provides important insights on knowledge and re-representation as phenomena of creativity.

This work emphasizes the following points:

(1) *conceptual structures of knowledge in visual reasoning in design*

Graphical reasoning in design is viewed here as a transaction between conceptual knowledge structures and design representation through a visual representational medium;

(2) *a re-representation theory for visual reasoning in design*

Based upon empirical research, and in order to explain the cognitive abilities enabling the sequential evolution of graphical representations, we propose a re-representational model of visual reasoning in design;

(3) *a re-representational model in design adaptation*

This model is highly relevant to cognitive and computational approaches to design such as Case-Based Design[15]. One of the priority research issues in CBD is the formulation of approaches and processes to the 'adaptation' of designs, or the modification of past design representations to fit a current design situation. Within the context of CBD, we propose the relevance of our re-representational model as a basis for formalizing adaptation;

(4) *re-representational theory as a foundation of studies of design creativity*

Modeling the interaction with visual representation media potentially contributes to the understanding of the relationship between concepts, knowledge structures and creativity in visual reasoning. The model of re-representation is, therefore, highly relevant to theories of creativity in design.

2 *The theoretical relevance of the re-representation hypothesis*

Cognitive and computational researchers are currently developing theoretical models which can assist in the analysis of sequences of representations and in the formalization of models. Particularly relevant to our research have been the psychological theories of *re-representation* with graphical re-representation. In modeling re-representation in design, we have exploited the Re-Representation Hypothesis (RRH), a psychological theory of creativity[6]. The RRH is a cognitive approach which explains creativity as an act of 'conceptual exploration through re-representation'[6–8]. RRH theory has been relevant to our research in design, since it provides a plausible model of the way in which human beings explore new modifications through *the externalization of knowledge structures in representations.*

The human capability to 'transform knowledge into representational structures' underlies the ability to make novel modifications and changes in those representations. Researchers in RRH theory have demonstrated that representations of drawings which are procedural are not flexible for innovative manipulations *until they are turned into explicit declarative re-representational form.* Karmilloff-Smith[6] demonstrates this cognitive process by the example of children's cognitive capability in drawing in the 'funny-man pictures study'. Re-representation of a form is possible only after the underlying representational structure of that form is externalized and made explicit in the drawing. In the case of the 'funny-man' experiments, an externalization of the man–body–schema is prerequisite to the distortions of the schema which are 'funny-men'. In the development of explicit representations of form, humans are able to transform implicit knowledge to explicit representational structure. This appears to enable novelty through modification and change which transcend, contradict, or depart from the generic representation.

We will demonstrate the direct relevance of these findings to design. Re-representation provides a changing pattern in the graphical medium. It is this pattern which is explicated in our research. If we are to model design as a process of re-representation, *we require the ability to model design through, and relative to, its declarative abstractions.* Following Karmilloff-Smith, we assume that the process of transforming graphical representations can be supported only according to *the declarative knowledge structures of design representation.* In design, these representational structures are frequently domain specific. An example would be the abstract formal structure of a particular design. This formal structure must first be made explicit in order that specific re-representational operations can be achieved

6 **Karmiloff-Smith, A**, 'Constraints on representational change: evidence from children's drawing' *Cognition* Vol 34 (1993) pp 57–83.
7 **Boden, M A** *The Creative Mind, Myths and Mechanisms* Cox and Weiman, London (1995)
8 **Dartnall, T** 'AI, creativity, representational redescription, intentionality, mental life: an emerging picture' Artificial Intelligence and Creativity, technical report, AAAI Press (1993)

on that structure. That is, in order to reformulate a design representation, an understanding of its structural content in terms of the underlying schema must be externalized. One of the contributions of our research has been to demonstrate the *cognitive ability of the human designer to recognize and externalize the underlying schema and structural content of designs*, and then to *work relative to the declarative knowledge which has been externalized.* Design creativity may be seen in this sense as the ability to innovatively re-represent the schema or the particular structural content of the externalized representation.

In the medium of sequential sketching we can observe the abilities enabling *change in a representational pattern which is supported by Knowledge structures*. Do there exist *domain specific knowledge structures*? According to Simon[9], drawings are employed for the externalization and the 'holding' of the various design representations which allow the designer to 'reason' with the design. Once externalized within the representation, the designer can focus upon aspects of the representation as a part of the design problem. For example, measure, or spatial order, are knowledge structures in plan development in architecture. Each knowledge structure may also be associated with its own representational medium. As we have observed in our experiments in architecture, formal and compositional knowledge such as modulation can be activated by making explicit a grid system in the graphic representation, and then modifying the representation according to the explicit ordering schema. Our research has identified such underlying domain specific schema and knowledge structures, and their role in design.

A further contribution of the research has been to demonstrate the significance in design of the concept of multiple representations. In design *a single representation generally has embedded various underlying multiple representational structures*. For example, various underlying ordering media such as grids or zonal structures, or functional orders and relationships are frequently implicitly present in design representations[15]. From our research, *the human designer appears to be capable of exploiting simultaneously these various underlying representational structures and of mitigating between them.*

This differs from the traditional RRH model in proposing that *multiple representational structures are implicit in design representations*. The designer may elect to make explicit the various implied schema as the design evolves. Thus, in design, the concept of multiple representation has a unique significance. In any design domain, there probably exist multiple underlying representational structures which may, in fact, be inherent in classes of design problems. What is significant in our research is the

9 **Simon, H** 'Keynote Lecture, AID '92' First International Conference at Carnegie Mellon University, Pittsburgh, Pennsylvania, USA (1992)

demonstration that *designers possess the cognitive ability to recognize, explicate and modify these structures, and to deal with these various representations simultaneously.*

3 *The methodological relevance of the concept of adaptation in Case-Based Reasoning*

Though diverse models of design relate to the developmental processes, the way design knowledge is structured and employed in such processes is, as yet, poorly formulated. The related research area of *computational models of design cognition* provides certain relevant concepts. One of the objectives of this field is to build the theoretical foundations of design cognition through computational modeling of design processes and reasoning. Work in the field generally exploits theoretical, experimental and computational research. Work in Case-Based Reasoning[10] and its application to design is directly relevant to the formulation of developmental processes in design. In the CBR view, adaptation is employed as a means of fitting an old solution to a new one, or evolving a new design by modifying an existing solution representation. In this work, the concept of adaptation developed in CBR is exploited to formalize transformations in the re-representation process.

The process of adaptation involves the re-use through modification ('adaptation') of the prior existing representational content of a design solution. Research on *case adaptation* in design[11] provides a perspective in the study and the modeling of cognitive sequences in the modification of case representations. We employ the term, design adaptation, in the following experiment description in order to distinguish and identify *the methodological content of the requisite knowledge and formalized steps of reasoning in a model of graphical re-representation.* In our research we exploit certain concepts derived from adaptation research in CBR in order to formally model the sequential transformations of graphical representations in design.

4 *A formal model of re-representation*

The theoretical assumptions developed in the first phase of the research were employed to construct an empirical study of designers' behavior in adaptive tasks employing design sketches and drawings. In the research we have attempted to explicate the multiple structures of knowledge underlying graphical representations and to demonstrate how they support modification in designs.

The proposed approach to adaptation is based upon the seminal concept of multiple-representation. The modeling of adaptation as a process of

10 Kolodner, J L *Case-based Reasoning* Morgan Kaufmann (1994)
11 Hinrichs, T R *Problem Solving in Open Worlds: A Case Study in Design* Erlbaum, Northvale, NJ (1991)

re-representation within the framework of this concept focused on a design task of the achievement of unique designs through adaptive processes. Subjects were asked to construct explicit representational structures implicit in a particular design form, in our case, an architectural plan. Adaptation processes in graphic re-representation were documented through protocol analysis. Employing the findings derived from an analysis of the protocols, a general model of adaptation of representations was developed. The resulting general model is considered to be valid for innovative and creative design as well as for routine design.

We describe the experiment, its objectives, research construction and findings. The findings were subsequently exploited in the construction of a general re-representation model of design.

4.1 Objectives and methods

The experiment was constructed to model design adaptation in the architectural domain which is strongly characterized by exploitation of graphical representations. The main goal of the experiment was to observe and record how designers actually manipulate given design representations in re-representational processes of adaptation. Adaptation was defined as the task of transforming a given design (representation) to meet changing constraints. The chosen task domain was spatial configuration in plan design. The complex nature of information in the graphical representation of designs raised several research issues. An additional objective of the experiment was to study the way designers deal with this richness of information in graphic representations, and the way they manipulate graphical symbols as abstract knowledge during the adaptation of design drawings.

The overall objective was to provide an account of the representations employed, the operations used and the way they were controlled in the adaptation process. The findings were subsequently analyzed and categorized for kinds of representational modifications, the strategies and operations employed and the way they interact in the process. Finally, it was possible to postulate the particular structures of representation which make graphic re-representation possible in these tasks.

Each of the designers in the experiment was requested to formulate and construct explicit representational structures implicit in the representation which, for him/her, enabled the making of changes. Subjects were also asked to record each of their graphical manipulations and rationale. Thus, both the representational structures employed in reasoning by the designers were identified and the resulting procedural manipulations were recorded.

The subjects were advanced students in architecture. They were required to adapt a given design on the basis of changed requirements. The required changes were purposely kept minimal in order to enhance understanding of the complex behavior in adaptation. The problem was to reduce the area of a given plan drawing by 20%. In such a limited problem statement students could easily explore different solution spaces and accurately record their decision-making rationale.

The subjects were asked to provide self-protocols recording explicit steps, actions and reasoning. The protocols were later formally recorded in a CAD graphics system to provide a sequence of re-representations supplemented by annotated textual explanations. Multiple representations were made explicit in the sequence. At a later stage, the group of participants contributed in the development of a joint model.

4.2 Assumptions

An underlying theoretical assumption is that the form of the graphic representation of designs and their amenability to adaptation are related. The form of representation encodes information and knowledge which support reasoning during manipulation. Therefore, in order to assist processes of reasoning in the adaptation of design drawings, and in order to be responsive to manipulations, graphic representations must be explicitly structured.

According to these main theoretical assumptions, the following concepts are proposed as the theoretical basis of the research.

4.2.1 Multiple representations as underlying abstraction levels

One definition of adaptation is that the current graphic state of the representation is manipulated until a fit is achieved with the new requirements. In order to support operations of re-representation we propose that graphic representations must be explicitly structured. The concept of *multiple representations as underlying abstraction levels* is the concept which we propose for accommodating semantic knowledge in graphics.

In the particular design task we can observe a structure of multiple underlying, or background, representations. These can be different kinds of generic abstractions of the design representation. Various works have begun to address the role of such abstractions in design and to demonstrate their utility in adaptation. For example, such descriptions include geometry-based descriptions of spatial aggregations, topological descriptions of spatial relations[12], grammar-based descriptions[13] and typological descriptions such as housing schema[14] etc. Other work on adaptation in CBR[11] has

12 **Baharat, D, Schmitt, G, Faltings, B and Smith, I** 'Case-based design in architecture' in **J Gero and F Sudweeks** (eds) *AID 94* Kluwer, Dordrecht (1994) pp 145–162

13 **Hua, K, Smith, I, Faltings, B, Shili, S and Schmitt, G** 'Adaptation of spatial design cases' in **J S Gero** (ed) *AI in Design '92* Kluwer, Dordrecht, (1992)

14 **Oxman, R E** 'Design shells: a formalism for prototype refinement in knowledge-based design systems' *Artificial Intelligence in Engineering* Vol 519 (1990) pp 2–8.

15 **Oxman, R E** 'Design case-bases: graphic knowledge bases for design workspace' in **M Tan** (ed) *CAAD Futures '95 Computer Aided Architectural Design* Singapore (1995)

pointed out the significance and role of general knowledge of adaptation procedures in a task. In this view, adaptive knowledge can be regarded as the ability to manipulate holistic designs which underlie the unique arrangement and relationships of components.

The range of processes of adaptation in design should preserve and exploit the significant aspects of a design by maintaining the internal consistency of its conceptual solution. In this experiment we have suggested to decompose a design drawing to its structures. The decomposition of design drawing into different structures of knowledge is, in fact, decomposition of different types of knowledge. Design drawings are usually not readily decomposable into separate representations, or structures. In order to isolate implicit representational structures it is important to identify the explicit representations which support visual reasoning. Since drawings are not explicitly structured according to those representations, it is significant to externalize them in re-representation. In order to assist processes of reasoning in the adaptation of designs we have experimented with the explication of underlying schema in graphic representations by requesting that the subjects make them (each abstraction level) individually explicit. In the final CAD formal reconstruction of the process these multiple representations were actually placed on separate layers. We have also attempted to generalize regarding those structured representations which recurred within the group of subjects, and may be considered relevant as domain knowledge.

4.2.2 *Internal consistency*

During adaptation, the design must remain internally consistent in order to satisfy various constraints. Constraints in evolution may be derived from different sources. We have identified two kinds of adaptation constraints: external given constraints, and internal derived constraints.

— external constraints are imposed from the problem definition, and are explicitly represented in the problem statement. For example, constraints between design and design environment, such as the site in architecture[12].

— internal constraints are derived as a consequence of an earlier design manipulation. For example, each change in components and their relationships can impose new constraints. Internal constraints are implicit constraints that are based on domain knowledge, their role is to keep the consistency among the multiple internal representations. Internal constraints are usually propagated by other constraints which emerge during the process. The ability to manipulate constraints can be regarded as a significant kind of adaptation knowledge. The designer must identify those reasoning processes that maintain the consistency of the internal representations.

If a design is to remain consistent, it should satisfy both external and internal constraints. It is the ability to handle consistency by the modification of structures, components and constraints at any time that characterizes the dynamic nature of the process of adaptation. Without controlling the impact of internal constraints between the different multiple representations, internal consistency cannot be maintained.

With each re-representation new internal constraints emerge. It may also be necessary to violate the constraints which are imposed by the new representation. In the experiment one goal was to understand the role of design constraints in re-representation and how the internal consistency and integrity of the design is maintained during its evolution. It is this ability to handle consistency by modifications under conditions of dynamic constraint propagation that characterizes one aspect of creative design.

4.2.3 Modification strategies and operations

Another research issue was to characterize modification strategies employed, or preferred by the subjects. Can these strategies provide a taxonomy for design adaptation? We believe that it is possible to define classes of strategies and operations. These are based upon types of modification relative to the underlying representational schema and constraints. In addition to modification of structures of a design, the ability to manipulate constraints can also be regarded as a significant kind of adaptation knowledge. For example, adaptation may be applied to constraints by weakening preferences and priorities. We have been able to draw only limited conclusions on this subject with our relatively small population of student designers. However, it appears to us that the cognitive mastery of graphical adaptation operations and schema modification strategies is one of the forms of design expertise.

4.2.4 The dynamics of re-representation

Each new adaptation opens the possibility for further interactions and new changes. In such an approach, diversity arises when opportunities for new interactions that can be exploited are recognized by the designer as an ever-changing pattern of possibilities.

5 Re-Representing the new from the known: a case study in architectural re-representation

In order to test and validate our assumptions, an empirical research was constructed. In the experiment, domain knowledge made manifest in graphical operations in a design task was studied. Representations in architecture tend to be task specific. Each task has its own representational system which supports reasoning processes within the task domain. The case study that was chosen was a house plan, the complexity of which was easily manageable by the subjects. The task domain was spatial configuration, or the formal and functional modification of the design representation of the plan. The subjects, who were 15 advanced level architectural students, were requested to do the following assignment. Given an existing design representation (plan drawing):

(1) To construct a set of underlying multiple representational abstraction levels for the given design. Each abstraction level suggested design operations associated with the type of knowledge or design principle. For example, an underlying abstraction such as an axis which is associated with symmetry may also be associated with operative knowledge such as morphological transformations relative to axial order. In the case study, certain classes of abstraction common in the domain were suggested as examples, while the subjects were requested to formulate other schema or abstraction levels which were relevant to their own re-representational operations. Certain typical schema or abstraction levels in the domain are (Figure 1):

underlying abstractions of order: for example: main rectangular axis, secondary diagonal axis system, main grid system, etc.

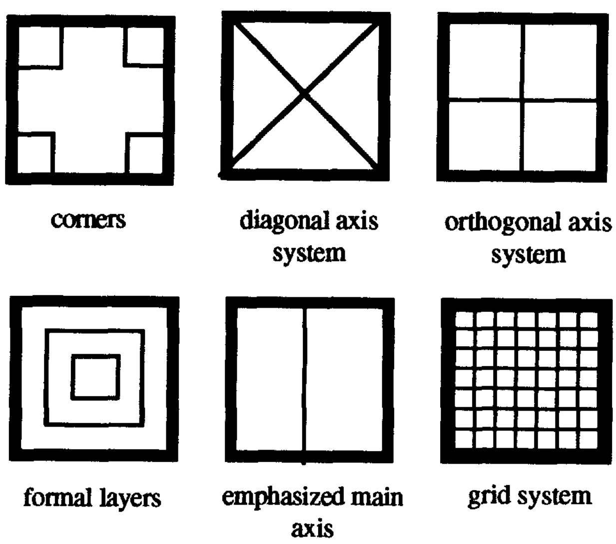

Figure 1 Abstraction levels as re-representational systems in design

typological schema: (typologies in housing design): for example, the knowledge of minimal and maximal dimensions of functional elements such as bedroom, bathroom, stairs etc.

underlying abstractions of order in schema: for example, principles of zoning, functional relations such as linkages between rooms, etc.

general design principles related to the task: for example, the reduction of corners, layering systems, emphasizing the main axis, etc.

(2) Given an external requirement, the subject was requested to identify design constraints and to select abstraction levels for re-representation which were related to these constraints. In this case, the external requirement was to decrease the area of the plan design by 20%. The subjects identified the constraints and most decided to preserve the topological relations of the design while effecting the re-representations.

(3) After first re-representations were effected, the designs were evaluated and faults were identified. For example, the functional types may have 'failed' functionally or formal principles such as the dimensions of grid system may have been 'violated'.

(4) At this stage the emerging internal constraints were identified and new re-representations were undertaken. In this way a cyclical process of changes propagated new constraints, which elicited subsequent modifications activated by the various knowledge sources.

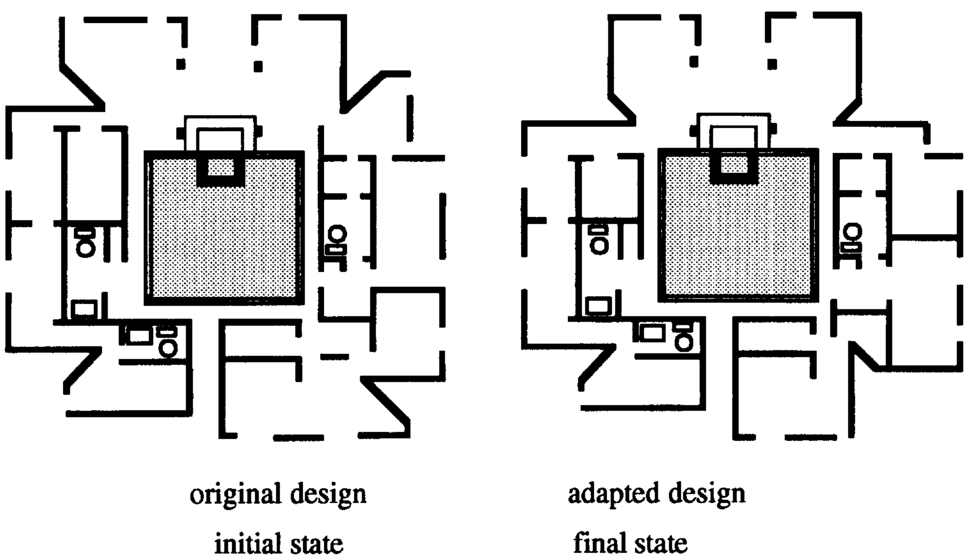

Figure 2 Initial and adapted final state

Figure 2 illustrates the initial state and the final state of this subject.

The re-representation sequence of the subject's example illustrated in this paper, included some twenty-eight recorded iterations. The first six re-representations are illustrated in Figure 3 and described below. Each re-representation generates a sequence of internal constraints which must be satisfied in the next re-representation and this continues in a cycle of sketches until all constraints are satisfied including the initial constraint.

— *re-representation 0 to 1*: (components affect structural schema)

Initial constraint is a reduction of size. The initial strategy was to start the reduction process on the holistic structure. The inner layer, one of a set of formal layers which contain functional zones (court) was reduced to a minimal functional size. This operation disturbed the consistency of the grid system;

— *re-representation 1 to 2*: (structural operation affects component integrity)

In order to reconstruct the regulation system the rest of the functional layers were shifted along the diagonal axial system. As a result some typological constraints emerged by changing the dimensions of functional spaces (entrance corridor) and architectural elements (fireplace);

— *re-representation 2 to 3*: (parametric modification)

The extension of a functional space (entrance corridor) was made in correlation with the diagonal system and axis;

— *re-representation 3 to 4*: (parametric modification of component)

Architectural element (fireplace) was transformed to original size in relation to central axis;

— *re-representation 4 to 5*: (topological and functional relationships)

The enlargement of one element (fireplace) has affected relations between architectural elements (column and fireplace), and required a subsequent change in related elements;

— *re-representation 5 to 6*: (formal system and parametric reduction)

The columns were shifted symmetrically and the two adjacent spaces were reduced.

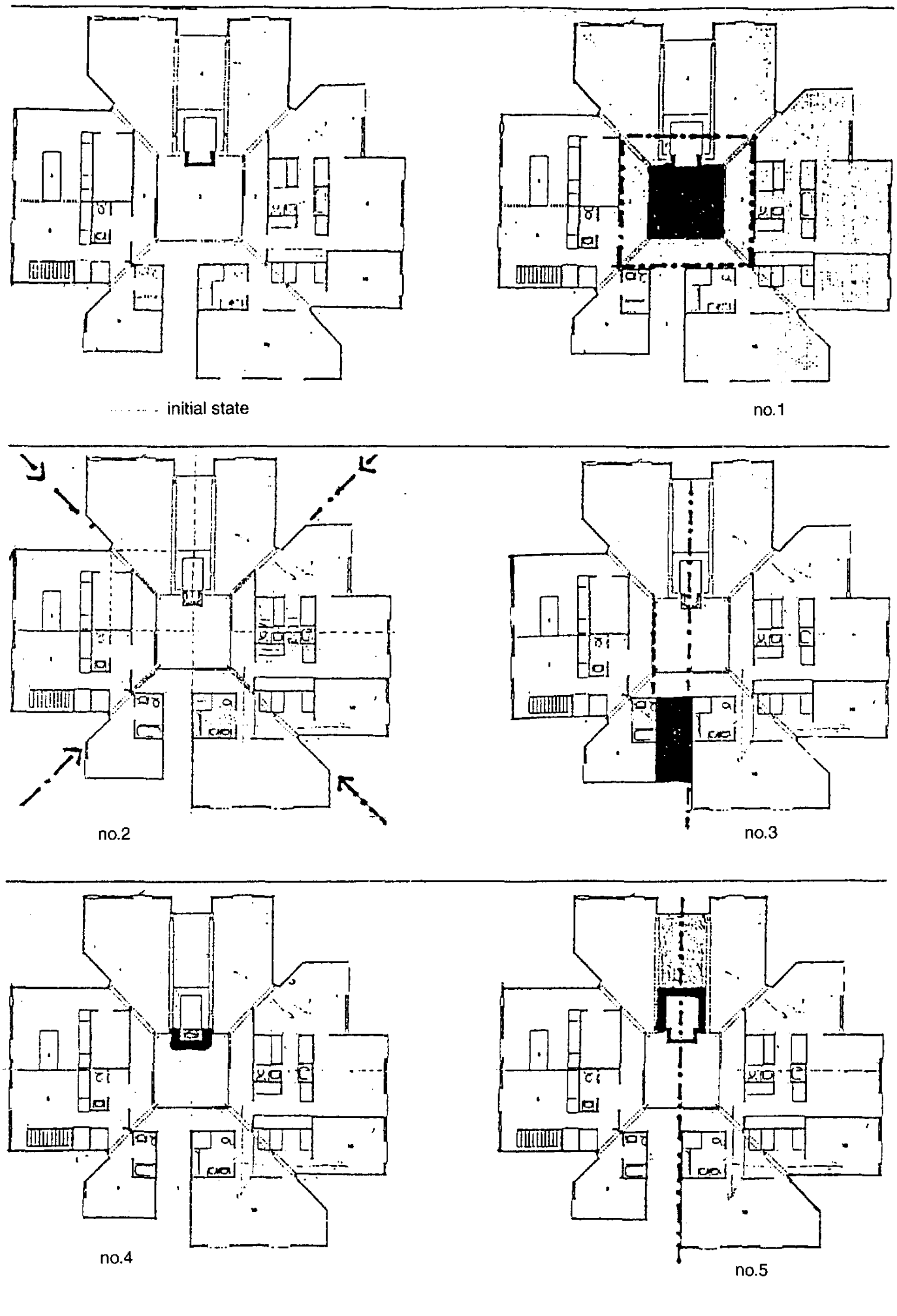

Figure 3 Re-representation on transformations (analysis done by Amos Wachman, Faculty of Architecture and TP, Technion)

5.1 Findings

Human designers were found to be able to extract various abstracted explicit representations of the existing design based on their own domain knowledge. These abstractions included typological schema, organizational principles, morphological principles, functional relationships, etc. Subjects were also able to externalize and categorize their graphic manipulations conceptually despite the fact that drawings tend not to provide explicit representational information to support such decomposition. Furthermore, the graphical re-representation of a design exploits this same knowledge in creating new representations.

From our research it appears that human designers utilize a personal hierarchical order of underlying conceptual structures such as grids, construction lines etc. These multiple schematic representations serve the designer as *supportive representations* for design manipulation. It is the structuring quality of these multiple representations and the explication of their individual internal constraints (the internal logic of the schema) which appear to support design manipulation.

The adaptation, or modification, of representations also appears to be *dependent upon generalized domain knowledge which is learned through design experience*. In the particular design to be adapted, this generalized knowledge enabled the externalization/construction of the underlying schema of the design. These (various) schema constitute the *multiple underlying representations* of the design. According to our findings, each design must have such multiple representations, if it is to support the manipulation of designs.

This abstract knowledge may be considered an inter-related system of domain specific representational structures. This finding is most relevant to the problem of appropriate representations for designs. Another of the most interesting observations was the contingent quality of the adaptation process. It was possible to observe how each new (modified) representation of the design introduced new modification strategies and operations, and even new structuring concepts. Recognition and maintenance of the internal consistency of the system of abstractions was found to be a characteristic of designers' cognitive ability. The ability to relate to this schema as a reference and to use or depart from it is a quality of the creative designer.

6 Towards a general model of reasoning in re-representation

In order to develop a general model we recorded the states of evolution of the design representations as well as the protocols of interactions between the designer and the semantic representations. The model is iterative and consists of the following main stages:

(1) External Constraints: identification of external constraints. External constraints are generally derived from the problem definition or redefinition.
(2) Initial Strategy: selection of re-representation strategy, including among others, structural modification of the schema, or component re-representation within the schema. In design there is always some form of hierarchical relationship between structure and component. Thus the selection of working within the abstraction levels of the schema structure, or modifying the schema depends upon the designer's evaluation of the external constraint. It may also be determined by personal design preferences.

It is the ability to handle consistency by the modification of structures, components and design constraints which is characteristic of re-representation. The strategy must be determined by the order in which to achieve modification. A constraint may be violated by adapting a value or by modifying the structure and it may also be possible to simplify a problem by relaxing a constraint.

(3) Representational Abstraction Layer: selection of layer of representation of schema, abstraction level, or individual component. In general, the constraints specify properties of the design that must be transformed. Such properties may be restrictions on values, or relationships between different components, and help to determine upon which representational layer the re-re-representation can be effected.
(4) Operational Method: selection of operational method associated with the representational layer. The constraint(s) guide the operations on a representation during the modification process. For example, typological substitution retrieves refinement methods; topology retrieves topological operations such as delete, insert and parametric operations; change in a formal system retrieves its own formal representational system.
(5) Evaluation: evaluation of internal consistency with respect to representational integrity, for example, in the formal structure of a design.
(6) Internal Constraints: identification of internal constraints which ensure internal integrity. The nature of a constraint affects the way re-representation may be performed. A re-representation strategy may also be invoked in response to the violations of the constraint.

(7) Selection: selection of active constraints according to priority criteria.
(8) Continue cycle.

Figure 4 describes some of the abstraction levels and their associated operational methods. The general model is schematically illustrated by one cycle of re-representation in Figure 5.

7 Summary and conclusions: the creativity in re-representation

Our work has explored the scientific means through which our own intuition about design can be transformed into the development of a theoretical approach. We have presented the theoretical and empirical foundations for re-representation models of adaptive design. In the empirical study an approach to the modeling of the design reasoning underlying re-representational processes through sequential drawing and sketching of re-representations has been described.

The empirical study has led to the construction of a general model of re-representation exploiting multiple representations of the abstraction levels in design. The model is based on the transformation of chunks of knowledge in design into explicit re-representational structures which can support the creative act of re-representation in a graphic environment.

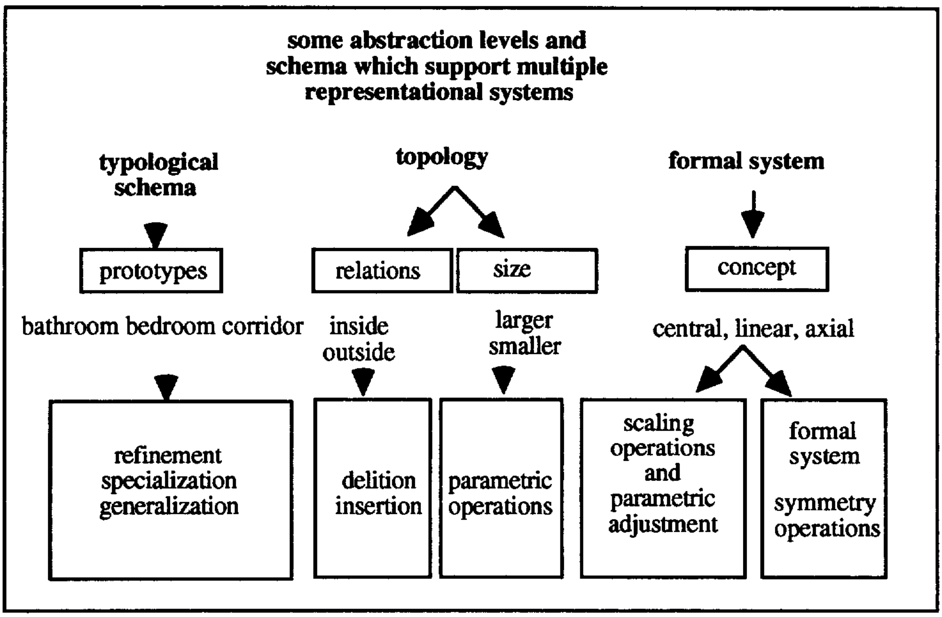

Figure 4 Abstraction levels and their associated operational methods

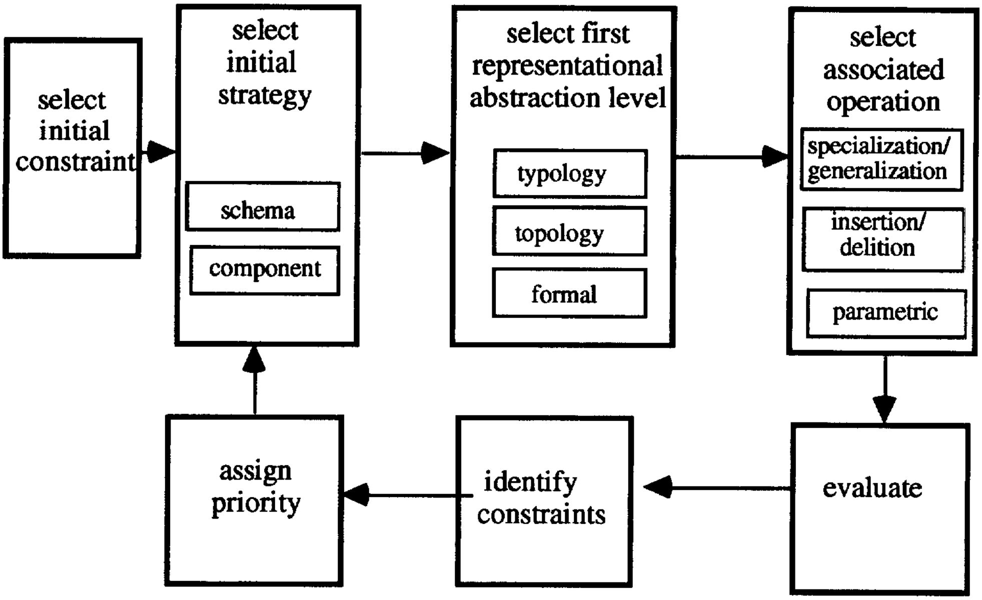

Figure 5 General model of re-representation

The sequential manipulations of graphical representations and the ability to re-describe must be considered one model of the creative act. Invention in design is, among other cognitive capabilities, considered to be influenced by the behavioral mastery of this process. Manipulation of representations through sequences of multiple re-representations is a keystone of the creative process which can result in designs of unexpected diversity and novelty. It is part of the paradox of creativity that through re-representation, the new can be made from the existing.

Our re-representational model of re-representation in design appears to provide one basis for a formal theory of creativity. The following concepts, which have emerged from our empirical studies, are relevant to the formal modeling of creativity.

— the human ability to transform implicit knowledge to representational structure enables modification and change;
— the capability to transform knowledge into representational structures underlies the ability to make novel modifications and changes within, or through, those representations;
— the establishment of the right representation may be considered to be a creative act;

Creativity can be explained in such an approach by demonstrating how designs can be accessed and transformed in novel ways. Furthermore, certain internal constraints of a re-representation in our model may necessitate the accessing of a new layer in another relevant design. This is one of many forms of 'explorative processes' which are common in creativity in design. These phenomena can be formally modeled within a multi-representational scheme of design as re-representation strategy.

Given that graphic re-representation in design is such an important and all pervasive phenomenon, we require more empirical and theoretical work in order to develop the basic concepts such as a taxonomy of types of knowledge structures, constraints or classes of strategies and modification operations in design. Lacking this level of basic concepts, even the description and analysis of the design protocols has been a difficult task. It is anticipated that these results will lead to a better understanding of human designers and ultimately strengthen our ability to development tools and methods to support them.

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