SIRN (Synergetic Inter-Representation Networks): an approach to design

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Abstract

Our aim in this paper is to examine the relation between design and cognition in light of two aspects related to these disciplines: (a) Cognitive science's negative attitude toward artifacts. (b) The fact that artifacts are the subject matter and end product of design. In our paper we firstly discuss cognitive science's attitude toward artifacts and show that it contradicts the reflective-interaction approach that currently dominates the discipline of design. We then introduce SIRN (Synergetic inter-Representation Networks) as an approach that resolves this contradiction by treating artifacts and their design as innately related to cognition. We close the paper by discussing further research directions.

SIRN (Synergetic Inter-Representation Networks): an approach to design

The status of *design* in the cognitive science

The status of *design* in the cognitive science is somewhat ambivalent. To a large extent this is due to cognitive science's attitude toward artifacts, which are the subject matter of the design process. Artifacts, as noted by Simon (1979), have a negative air around them – one doesn't want artifacts in one's data or empirical results. This is so in science in general and this is so in cognitive science. Its emergence was associated with an attempt to transform the "soft" study of mind, thought, imagination and language into a "hard" empirical and analytical cognitive science –*The Mind's New Science* (Gardner, 1987). The negative attitude toward artifacts was (and still is) typical mainly of classical cognitivism according to which artifacts are simply 'not cognitive'. They are the product of human actions, which are the outcome of cognition, and as such bodily artifacts, but not cognition itself. The following section by Chomsky on external and internal languages (E- vs. I-languages respectively) is indicative:

"E-languages are mere artifacts. . . the concept appears to play no role in the theory of language. . . The technical concept of E-language is a dubious one in at least two respects. In the first place, .. *languages in this sense are not real-world objects but are artificial*, somewhat arbitrary, and perhaps not very interesting constructs. In contrast ... statements about I-language ... are true or false statements about something real and definite, about actual states of the mind/brain and their components ... "(Chomsky 1986, 26-7, italics added).

From this view on cognition and artifacts follows two possible positions of design in relation to cognition. First, design, like thinking, is part of cognition while bodily action and artifacts are not. Here the process of design is essentially distinct and separated from its product – the artifact. Second, design is part of the production of artifacts and therefore it is not cognitive.

Cognitive science's negative attitude toward artifacts is currently changing. A growing number of studies depart from this sort of hard cognitivism. Rumelhart et al (1986) and Cole (1996) neo-Vygotskian approaches, Edelman's (1992) TNGS (Theory of Neural Group Selection), Johnson's (1987) and Lakoff's (1987) approach of *experiential realism*, Donald's (1991) notion of *the externalization of memory*, and the recent pragmatist views of *embodied cognition* (Varela et al 1994) as well as the *action-perception* approaches (Thelen 1995, Thelen and Smith 1994, Kelso 1995, Freeman 1999) among others, all tend to see the cognitive system as including the body and its interaction with the environment and/or elements in it. These approaches suggest that in certain tasks and contexts cognition is confined to the brain; in others to the whole body and in some tasks and contexts the cognitive system includes the brain, the body and even stand-alone artifacts in the environment. The latter possibility refers to cases where artifacts function as an extension of the body – a view suggested by Gibson (1979) and reproduced here in Fig. 1.

From the above perspectives it follows that bodily artifacts are part of cognition while stand-alone artifacts are only in cases where they function as an extension to the body. In themselves, however, stand-alone artifacts and the process of their production are not cognitive. This view does not change the status of design in the cognitive science, at least not the design of stand-alone artifacts.

Figure 1: Scissor as extension of the body

A concise history of design methods: the two major approaches

Over the last forty years, developments in cognitive science have been significant to different human related fields including design and urban design. Influenced by the classical cognitive sciences of the 1960s, the so-called 'design methods' approach proposed analytical/rational problem solving techniques. The main concept was that designers should be capable of predicting the effects and consequences of their designs, and describe the actions and steps that are necessary to achieve them. The design methodology movement paid little attention to the design solutions per se, and became much more concerned with the large network of predictions and specifications through the different phases of the design process (Jones, 1980; Lawson, 1980). With the aim of formalizing design processes, the design methods movement proposed *prescriptive* models of design, which were based on the idea that the different steps in the design process can be optimized and defined a priori. Thus, a strong emphasis was set on logical and objective analyses of the design process. A main example of this approach was the revolutionary paradigm presented by Simon in the early 1970s (Simon, 1973). In his view, design is seen as a rational search process, in which the design problem is defined by a problem space. This problem space is carefully explored while searching for a 'satisfying' design solution. However, Simon's and other similar approaches did not take into account the individual properties and characteristics of the designer that they were supposed to support. According to Dorst and Dijkhuis (1995), the main emphasis of the 'rational problem solving approach' was set on the process components of the design activity, but the movement was unsuccessful to understand the knowledge structures of what designers perceive and think. As a consequence the design methods movement failed to support real design problems.

In recent years, the study of *cognitive processes* concerned with problem-solving activities began to capture the interest of design researchers. It was postulated that while solving problems under controlled conditions, individuals might be able to externalize representations of their internal mental processes. In contrast to the rational movement the major attempt of which was toward prescriptive design models, recent studies proposed descriptive design models that strongly emphasise the cognitive dimension of design (e.g., Cross, 2000). The main idea was to focus on the interplay between the designer's internal and external representations in the early stages of the design process An example is the pioneering work of Schon (1983) on design as *reflection in action*. Schon argued that the view of design as a rational problem solving process weakened the understanding of unique design problems. Basing his approach on a constructionist view of human

perception-and thought processes (Dorst, 1996) he perceived design as a reflective conversation between the designer and the external situation (named the environment). By identifying relevant aspects from the design problem, the designer chooses a problem situation, or frames the problem according to a particular situation, and develops a possible solution while evaluating and reflecting upon the design outcome (named the design artifact). These enable him/her to check his/her understanding of the problem situation, to create a new framing of the situation. And to verify his/her interpretation of it on the basis of prior experiences. Current cognitive research based on the analysis of design thinking and design behavior, saw in Schon's approach a potential tool for enhancing our understanding on the design process.

Discussion

As noted above, from the point of view of cognitive science, stand-alone artifacts are essentially external to the cognitive system and process. In some circumstances they function as an extension of the body, but in themselves they are not cognitive. Such a view corresponds to Simon's paradigm on design as a rational problem solving process, the end product of which is an artifact. Schon's reflexive conversation view is somewhat different. The designer "talks" to the environment and the latter "talks back" to the designer. Here the designer (person) and the designed (artifact) form two parts of a single design system.

Schon's main concern is the process of design and he therefore makes no claims about the cognitive process. Our concern is to look at the process of design from the point of view of cognitive mapping and the cognition of large-scale artifacts such as cities. From this perspective we suggest, first, that the 'reflective conversation' view on design contradicts cognitive science's view on artifacts. Second that it indicates the possibility to understand the cognitive system as including in addition to *perception* and *action* also *productions* (Fig. 2). Third, that the action-perception-production view of cognition implies that design is an innate human capability active in the production of small as well as large artifacts such as cities. These three suggestions are derivations from the notion of SIRN that is introduced next.

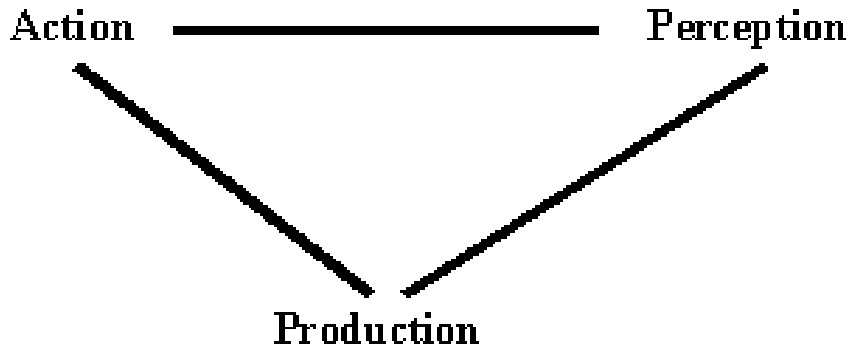

Figure 2: Action/Perception/Production view on cognition

SIRN's four propositions and design

SIRN is an approach to cognition suggesting that artifacts and the process of their design and production are part of cognition (Portugali, 1996; Haken and Portugali, 1996). In this section we introduce SIRN and show its implications to design. We do so by examining the SIRN's four basic propositions.

1. *Humans have an innate capability for representation that comes in two forms: external and internal*. Internal representations are the outcome of brain processes the end product of which is various forms of information (visual, olfactory, haptic, lingual, etc.,) that are enfolded (i.e.

represented) in the matter of the brain. External representations refer to behavior or action that represent internal representations. External representations can be further divided into *bodily* and *stand-alone* representations. Bodily representations (mimetic, lexical, etc.) are made by the body and never extend beyond it. Stand-alone representations are made by the body, but extend beyond it to become stand-alone artifacts. Stand-alone artifacts are the products of design processes. From this follows three interrelated corollaries: (1) Design is an innate human capability. (2) Humans perceive, learn, think and execute many cognitive operations by designing and producing artifacts. (3) Humans design not only in order to achieve goals or intentions, but first and foremost because they are "born to design" – their innate capability to design and produce artifacts allows them to achieve many of their aims, intentions and goals by means of the design and production of artifacts.

2. Many cognitive processes, those associated with the production of artifacts included, evolve *as an interaction between internal and external representations.* This is typical of complex cognitive process that are subject to "The magic number seven plus or minus two" that according to Miller (1956) "… limits our capacity for processing information" in short term memory. In his paper Miller discusses several tactics by which the mind/brain may overcome this constraint. Haken and Portugali (forthcoming) suggest that another trick the mind/brain/body uses to overcome this constraint is by means of external representations and the production of stand-alone artifacts. The production of artifacts and by implication their design are thus integral parts of the cognitive process of humans. This is typical of sequential cognitive processes that evolve by means of an interaction between emergent internal and external representations. Thus, one starts to develop a thought, or an idea by first constructing it in mind in the form of an internal representation. Then one develops it a few steps further in short-term memory. When the threshold of Miller's "magic number 7" is reached, one externalizes one's internal representation in the form of a talk, a written sentence, or a sketch, observes how it looks, etc., then internalizes it again as a starting point for further development in mind and so on in an interplay between internal and external representations.

3. *The boundaries of the cognitive system should be perceived as distinct from the boundaries of the brain (the skull) and the body (skin).* This is the logical conclusion of propositions 1 –2. In design tasks, the boundaries of the cognitive system correspond to the boundaries of the design system. The latter includes the designer's mind and body, the design action and the produced artifact. That is, the cognition-design system is composed of action-perception-production.

4. *The cognitive system is a self-organizing system the dynamics of which is captured by the synergetic approach to self-organization. Self-organization* is a fundamental property of *open* and *complex* systems that attain their order spontaneously and are typified by phenomena of non-causality, non-linearity, instability and chaos. Such systems are open, in the sense that they exchange matter, energy and information with their environment, and complex in the sense that their large number of parts are interconnected in a nonlinear fashion by a complex network of feedback loops (Portugali 1997, 1999).

Synergetics is Haken's (1983, 1987) theory of self-organization. The theory focuses on processes by which the local interactions between the many parts of a system give rise to qualitative changes at the system's macroscopic state. According to synergetics such a qualitative macroscopic change happens when a given internal or external *control parameter* acting on the system triggers a chaotic movement and interaction between its many parts. This chaotic movement enfolds several systemic order states that co-exist and in this respect "compete" among themselves. When the control parameter crosses a certain threshold, the hitherto chaotic form of movement and interaction suddenly and spontaneously give rise to a coherent movement and interaction where all the parts behave in concert. This coherent movement is termed *order parameter,* and the process by which

the many parts abruptly “obey” the order parameter and in this way support and reproduce it – the *slaving principle*.

Synergetics was applied to the domain of cognition and brain functioning (Haken 1979, 1990, 1991, 1996, Kelso 1995). The basic proposition here is that the brain and its various cognitive systems are self-organizing systems.The paradigmatic case-study here is pattern recognition by means of associative memory: the cognitive system is given a few features of a certain pattern (i.e. face) referring to one out of a repertoire of patterns stored in memory. This triggers a process of self-organization in which several order-states emerge and enter into a competition. This competition is resolved when a certain order parameter "wins", enslaving the various features by means of associative memory, and a recognition is established.

A similar process typifies the construction of cognitive maps (Portugali 1990; Portugali and Haken 1992; Portugali, 1996), behavior and action (Kelso 1995). With respect to the latter two, synergetics suggests seeing the brain, mind, bodily behavior and action as open, complex, task-specific and context-dependent systems that achieve their coherence spontaneously, by means of a complex co-operation and interaction between their many parts. The interacting elements of that system are, therefore, both internal and external.

The SIRN basic model and its three prototypes as models of design

Haken and Portugali (1996) have cast the notion of SIRN into the formalism of *synergetics.* They have done so by developing the SIRN basic model. The model was inspired by Bartlett‘s (1932/1961) *scenarios of serial reproduction* devised by him in his book *Remembering.* A typical Bartlett scenario evolves like this (Fig. 3): a test person is given a text or shown a figure and is asked to memorize it. He or she is then asked to externally reproduce the text or figure out of memory, by rewriting the text or re-drawing the figure. This externally represented text or figure is given to another test person and so on. The usual result of such scenarios is that after several strong fluctuations in the reproduction, the text or the figure stabilize and do not change much from iteration to iteration. Bartlett reports that the same happens when the experiments are carried out with a single person. This experiment includes all the ingredients of synergetics and inter-representation and can thus be regarded as a paradigm case study for the operation of SIRN (Portugali, 1996; Haken and Portugali, 1996): A play between internal and external representations that emerge spontaneously out of the dynamics as ad-hoc entities, strong fluctuations at the start and an ordered state that eventually “enslaves” the interaction.

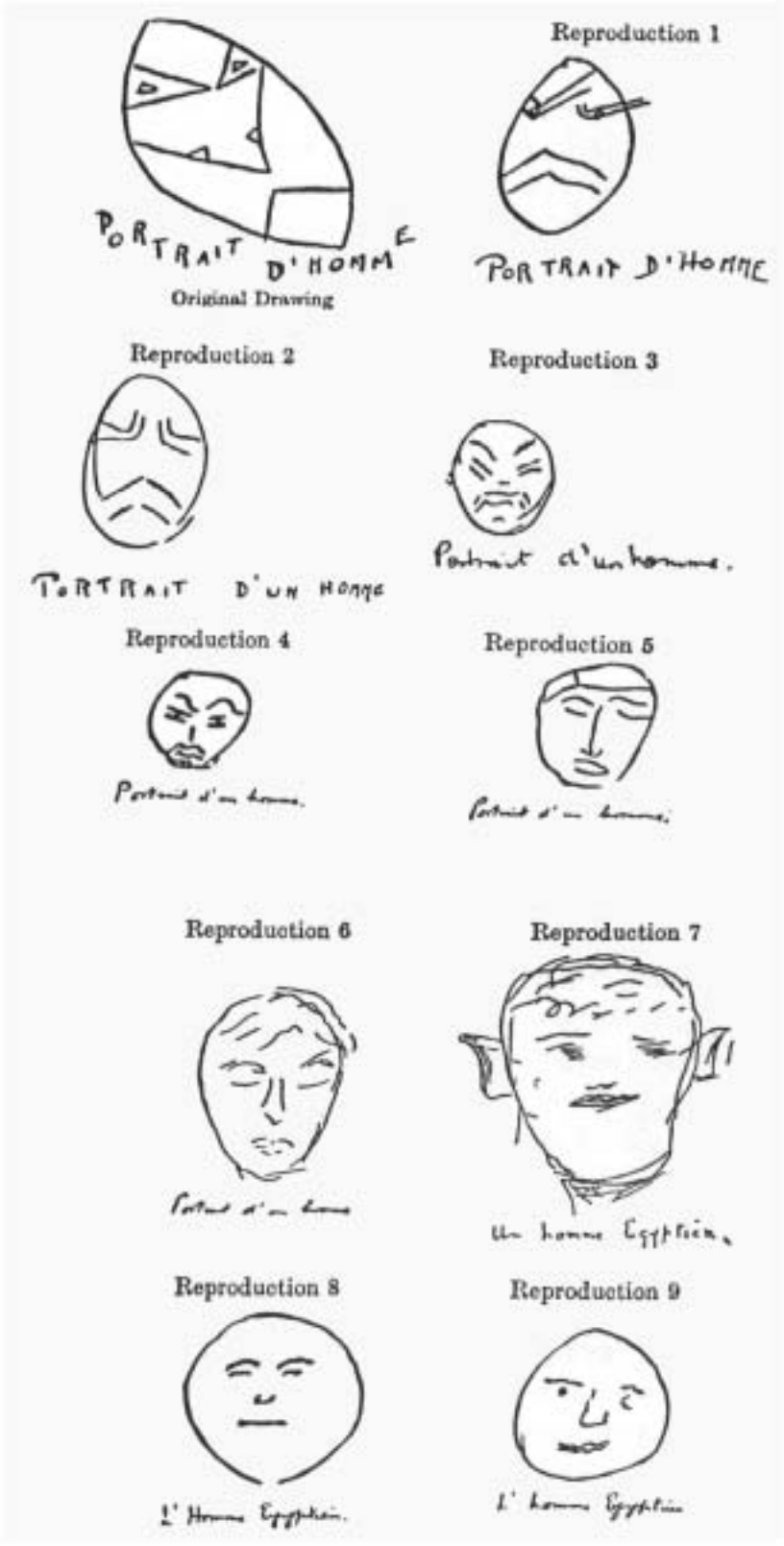

Figure 3: A typical Bartlett scenario

The basic SIRN model is described in Fig. 4. In the context of the present paper this model refers to a designer that is subject to two kinds of input information: internal information that is coming from the designer's mind/brain, in the form of ideas, images, thoughts, and the like, and external

information that is coming from the environment via the senses, the designer's body and/or the information afforded from stand-alone artifacts. The interaction between these two flows gives rise to an order parameter that governs both the designer's action, and the information that feeds back from the artifact produced to the designer's mind. The order parameters are determined in line with the theory of synergetics as described above.

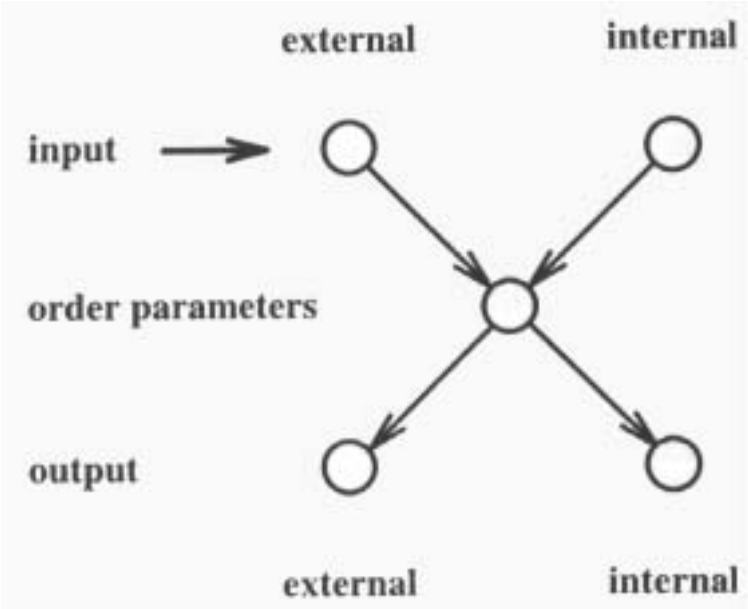

Figure 4: Basic SIRN model

The basic SIRN model is applied to specific case studies by means of its three prototype sub-models of design: (1) *Intra-personal*, that describes a solitary designer working by him/her self. (2) *Inter-personal* that refers to a sequential process involving several solitary designers not necessarily aware of each other. (3) *Inter-personal with a common reservoir* that describes a group dynamics by which several designers are working simultaneously and publicly on a large-scale artifact.

The Intrapersonal submodel

The intrapersonal submodel is described in Figure 5. It refers to the Bartlett's serial reproduction experimented with a single person or to a solitary designer engaged in some creative work. A nice illustration for this process is Brancusi's Kiss that evolved as a typical process of interaction between internal and external representations (Figure 6). As can be seen, similarly to the Bartlett scenario, here too the figure is gradually transformed from a realistic to a highly schematized geometrical shape. This by means of an interaction between internal representations in the form of images, ideas, etc., that emerge at the artist's mind, and external representations that represent the artist's ideas and images as they take a specific shape in the material with which the artist is working. What is specifically interesting in Brancusi's Kiss is that its final reproduction (The Gate of Kiss) was imbedded in the cityscape of Bucharest, thus illustrating how a very personal SIRN process 'goes public'.

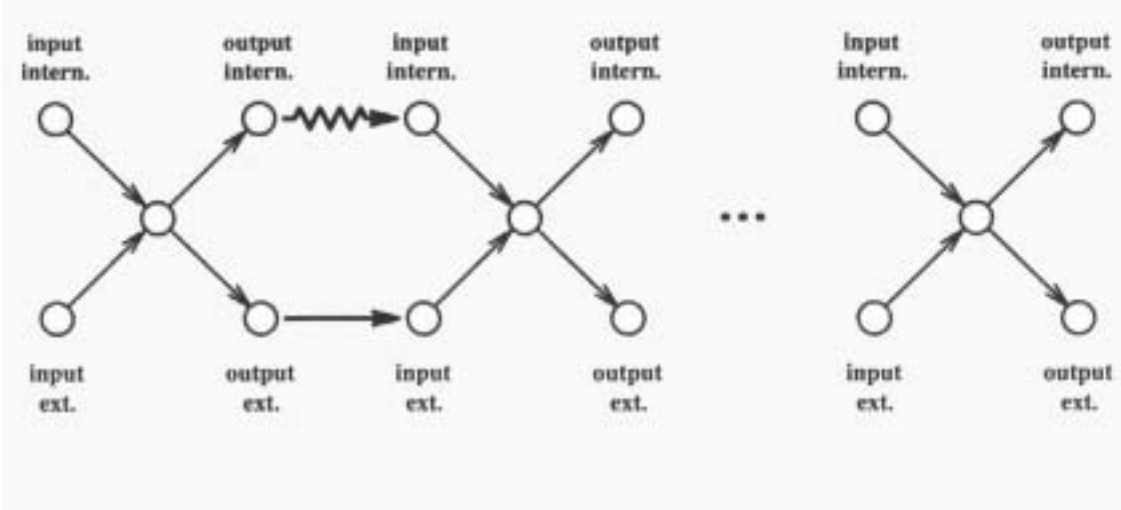

Figure 5: Intra-personal sub-model by means of SIRN

Figure 6: The evolution of Brancusi's Kiss

This process is typical also of the role of sketches in design. Free-hand sketches are frequently produced by architects and designers at the early stages of the design process. A sketch is characterized by having an ambiguous and amorphous nature that serves the purposes of clarifying existing design ideas stored as internal representations in the mind, and generating new ones through external representations (e.g., Casakin, 1998; Do, et al, 1999; Evans, 1989; Fish and Scrivener, 1990; Goldschmidt, 1992). Researchers such as Suwa and Tversky (1997) explored the sketch as a means for gaining a better understanding of how subjects perceive and cognize content and process components while solving a design problem. Goldschmidt (1994) proposed that the design process often starts with vague ideas that are gradually elaborated and structured. In this process of elaboration sketches can aid in generating and strengthening them. Moreover, different features of a yet non-created artifact can be produced, transformed, and externalized through sketches for communication and evaluation. Thus, a critical aspect of sketching is the possibility of generating sequential and abstract design representations before they are clear in the mind. This enables the identification of relevant from irrelevant information, and on the other hand, the reinterpretation of previously unforeseen or unpredicted information. As the sketching activity evolves, an interactive dialogue or reflective conversation is established between the designer internal representations retrieved from memory, and his or her produced external representations that 'talk back' to him (Schon, 1983; Goel, 1995) until a suitable design solution is reached. Goldschmidt, (1999) referred to this phenomena as the backtalk of self-generated sketches, which points to the designer capability to read meaning, and discover new interpretations from his or her own external representations. Verstijnen (1997), and Verstijnen et al (1999) claimed that when designers have difficulties of interpretation in mind, the use of the sketch plays an important role as a tool for aiding idea reinterpretation and problem restructuring. An example of a practical use of the sketch is illustrated through the work of the architect Jorn Utzon (Figure 7). His sketches are not intended as the production of just beautiful drawings, but made with the aim of understanding a design problem, and proposing a design solution (Lawson, 1994). With the purpose of constructing the roof of the Opera House in Sydney, a rich sequence of sketches are developed to learn about engineering structural aspects. During this process, a sketch establishes a dialogue with another, as ideas develop and gradually evolve from evocative conceptual sketches related to rather organic forms, to more detailed and refined representations.

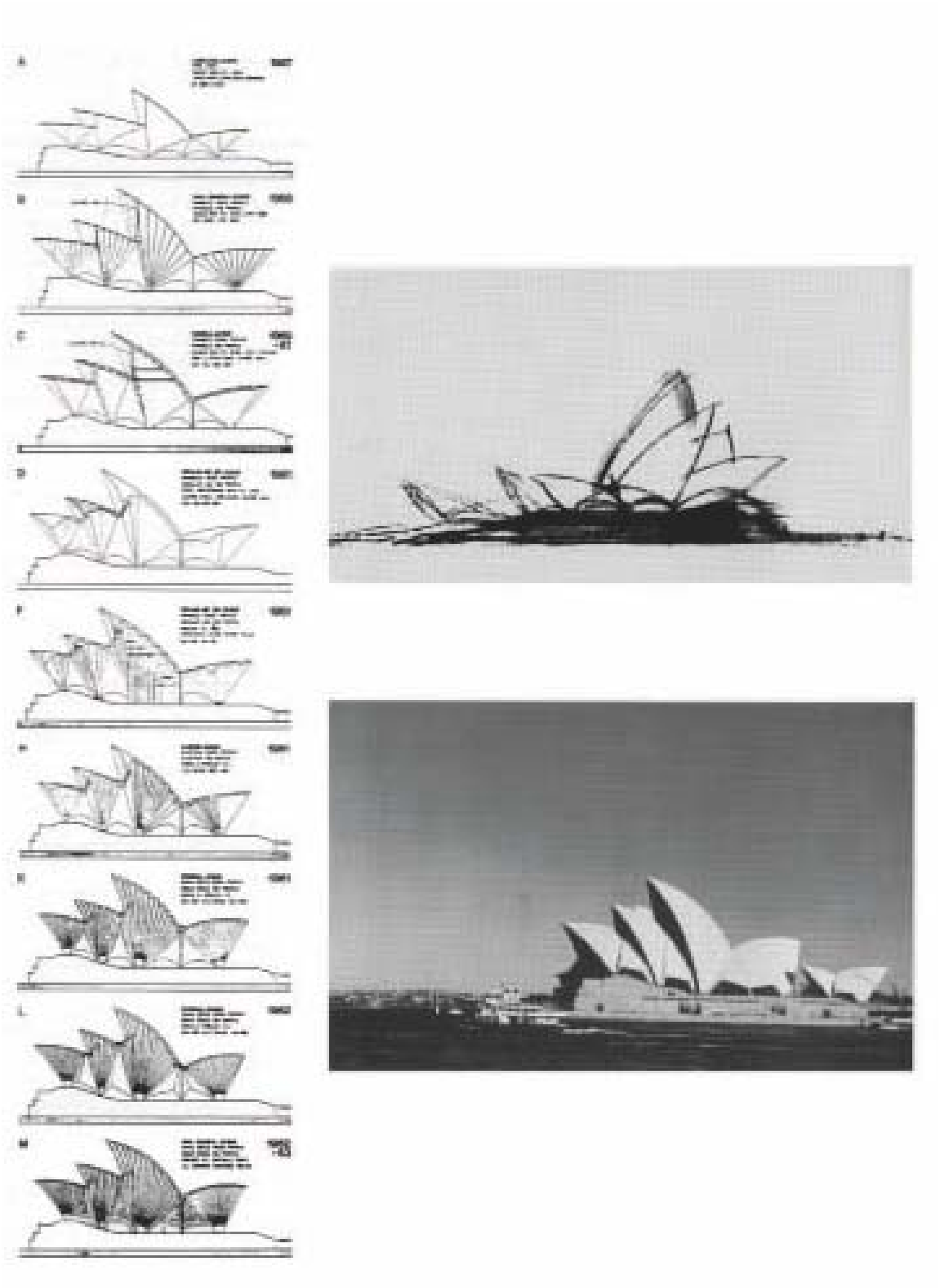

Figure 7: Sketches from the Opera House at Sydney, by Jorn Utzon

The difference between the examples of Brancusi and Utzon sketches is that in the case of sketches the play between internal and external representations continues until the end product – the artifact – is completed; after this stage the design process ends. In Brancusi's case "the play never ends" – the artifact has a status of a sketch.

The Interpersonal process

This is the classical Bartlett scenario, as illustrated above in Figure 3. A typical experiment starts, as noted, with a given external input and proceeds with a sequence by which each person's externalized reproduction of the remembered input becomes an input to the next person to remember and externalize, and so on. As above, after several initial steps that exhibit major changes from one reproduction to the other, the story or the drawn figure stabilizes and does not change significantly from iteration to iteration. In terms of synergetics we assert that a certain order parameter has enslaved the system and brought it to a steady state. This interpersonal process implies that several persons, with their individual-subjective cognitive systems, participate in producing an externalized collective cognitive product, without being aware of their collective enterprise. As this sequential process evolves, and its collective product constructed, each individual's externally represented reproduction gradually becomes "more" collective and so does each individual's internally represented remembering. The individuals engaged in the process are thus being ‘enslaved’ by the collective order parameter that emerges in the process. Figure 8 graphically describes this interpersonal scenario by means of our SIRN model.

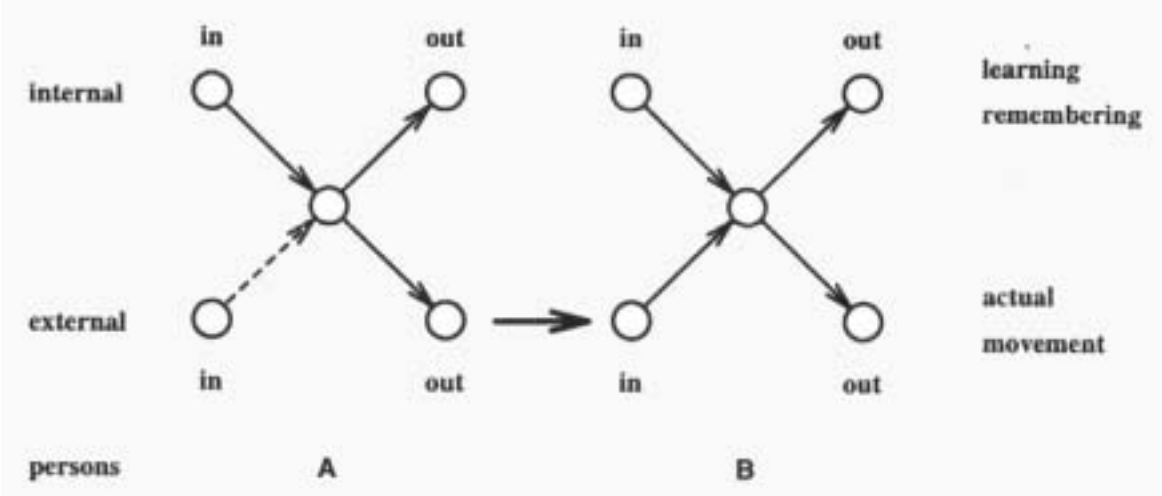

Figure 8: Interpersonal sub-model by means of SIRN

An example in the domain of architecture can be the design of complex artifacts such as public buildings by a design team composed of structural engineers; environmental engineers; interior designers; etc. As the design process develops, the problem is decomposed into sub-problems in order to answer initial programmatic requirements (Cross, 2000). In doing so, designers establish an interactive dialogue between their own internal and external representations related to their domain of expertise, and a sequential interplay between external representations of the other designers. A synergetic, self-organized system among the various designers thus emerges and develops until a design solution is found.

An additional example is Rossi’s (1986) concept of urban ‘typologies’ as ‘perpetuating permanencies’ capable of adaptation to modifications performed by different designers through history. According to Rossi, socially relevant buildings were able to last because they managed to keep their external formal attributes while adapting their internal functions to new programmatic requirements, new conditions, and uses. While the design of the building evolves or changes, a sequential–temporal inter-play of external and internal representations is established between different architects that are not necessarily aware of each other.

Interpersonal with a common reservoir

In the intra- and inter-personal sub-models the process depends fully on the biological memories of individuals. Here the process depends partly on biological memories, but partly also on externalized non-biological memory termed a *common reservoir*. This common reservoir of external, artificial and non-biological memory, might take the form of texts, Internet, buildings or whole cities. To illustrate and study such processes a set of experiments –*city games* – was devised (Portugali, 1996b). Their essence is a process of sequential reproduction that is interpersonal, collective, and *public* – the participants observe the game as it develops. Each player is given a 1:100 mockup of a building, and in his/her turn is asked to locate it in the virtual city on the floor. In a typical game (Figure 9), the players observe the city as it develops, and in the process also learn the spontaneously emerging order on the ground. After several initial iterations a certain urban order emerges. The participants internalize this emerging order and tend to locate their buildings in line with it. Such an experiment includes all the ingredients of the SIRN process: a sequential interplay between internal and external representations, the emergence of a collective complex city as an artifact, and a typical synergetic process of self-organization as demonstrated below. It is typical in such games that after a few initial iterations an observable urban order emerges, the participants internalize this emerging order and tend to locate their buildings in line with it.

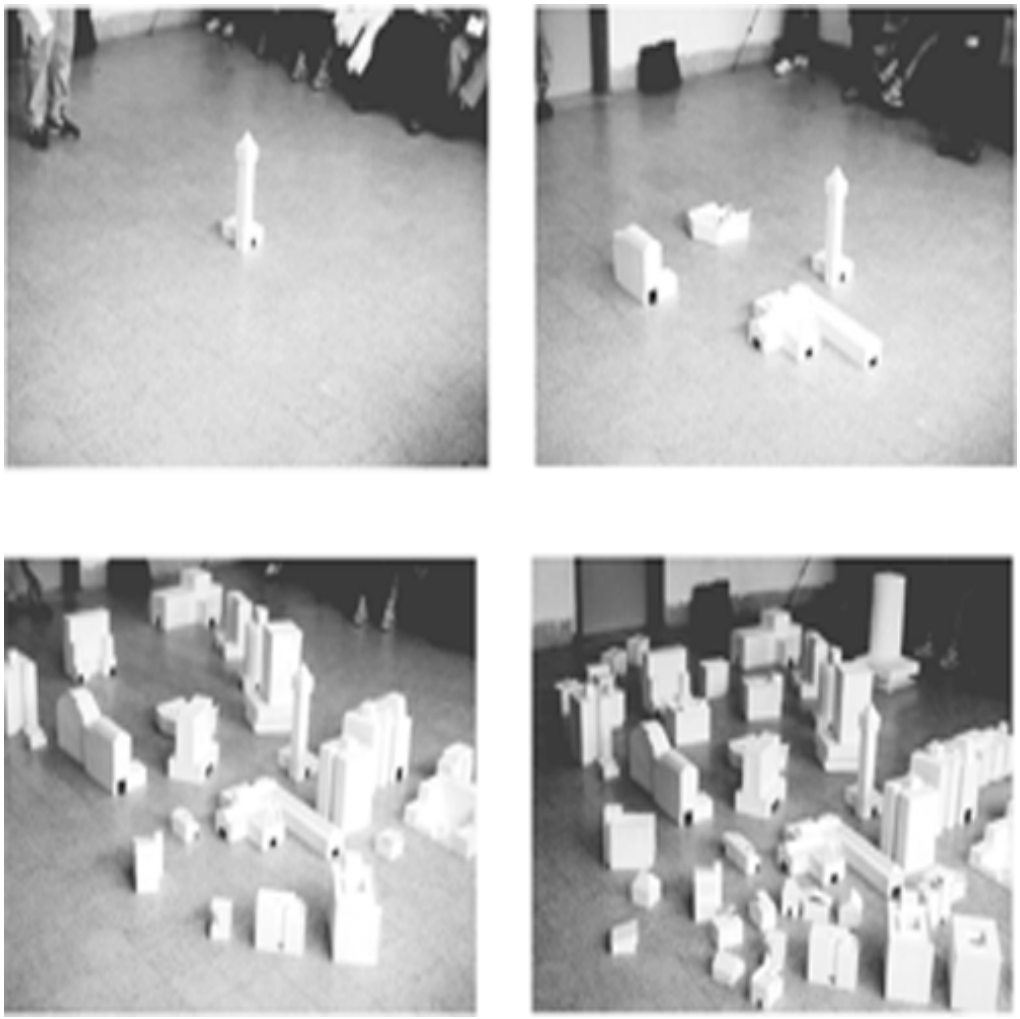

Figure 9: Four snapshots from a typical City Game

Figure 10 illustrates graphically this public-collective SIRN sub-model. Each individual player/agent is subject to internal input constructed by the mind/brain, and external input which is

the legible information coming from the common reservoir. In the above city game it is the virtual city on the ground. The interaction between these two forms of input gives rise to a competition between alternative decision rules that ends up when one or a few decision rules “wins”. The winning rule(s) is/are the order parameter(s) that enslave(s) the system. The emerging order parameter governs an external output, which in the city game is the player’s location action in the city, and an internal output, which is an information feedback loop back to the mind/brain.

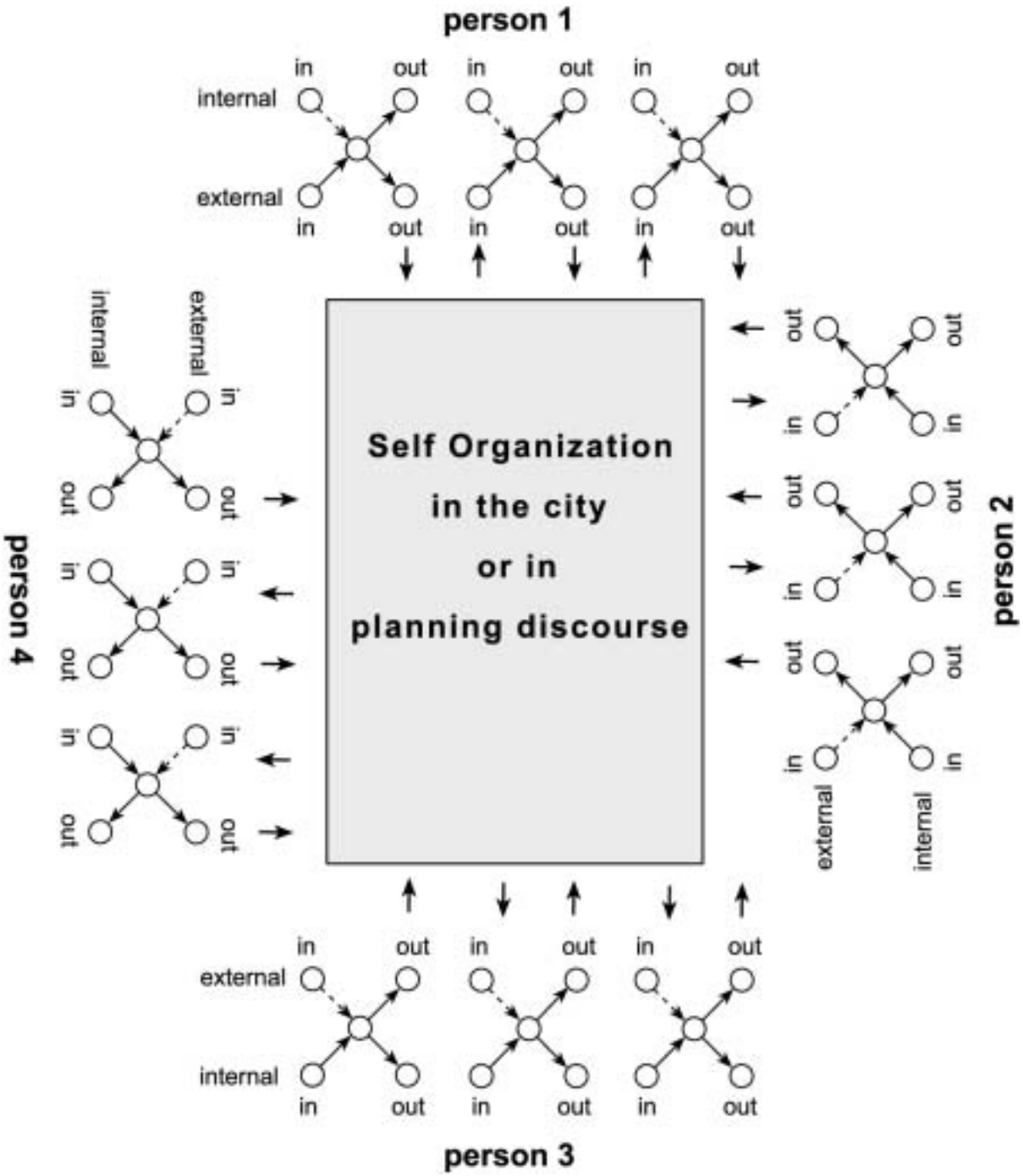

Figure 10: Interpersonal with a common reservoir sub-model by means of SIRN

Design and self-organization

From the above follows a view of design as essentially a self-organizing system. On the face of it the two notions ‘design’ and ‘self-organization’ contradict each other: Design is commonly regarded as an intentional, and as such externally organized process, in contrast with spontaneous self-organized process. But there is no contradiction here. To see why let us look once again at the various examples introduced above. Consider first the paradigmatic case study of Bartlett scenario of serial reproduction (Fig. 3). This scenario includes all the ingredient of a self-organizing, cognitive, SIRN system: emergent internal and external representations, strong fluctuations at the start of the process, an emerging order parameter in the form of a schemata of an abstract shape of a face that eventually enslaves the many parts of the system and brings it to a steady state. A similar process takes place in the cases of Brancusi’s Kiss (Fig. 6), and Utzon’s sketches (Fig. 7). The

latter two case studies should be taken in conjunction with Miller's magic number 7 discussed in Proposition 3. As a consequence of the number 7 constraint on short-term memory, a design idea or intention are usually not yet the final product but its trigger. The end product, that is to say the artifact, emerges as noted above out of the SIRN play described above. Many design processes, in particular those associated with complex artifacts, thus involve a sequential, self-organizing processes.

The case study of the city game (Figs. 9, 10) refers to a much more complex process of self organization. As elaborated recently in *Self-Organization and the City* (Portugali, 1999) the city is a *dual* self-organizing system: On the one hand, the city as a whole is a self-organizing system whose elementary parts are the many agents operating in it. On the other, each of the agents operating in the city is itself an open, complex and as such self-organizing system. The agents act and interact, with and in the city, among other things according to their cognitive maps of it. This interaction give rise to the city dynamics and structure, that once emerges feeds back to the agents' cognitive map and so on in a process of circular causality and reproduction. The city in this respect is similar to language. As in language each of the parts is a self-organizing system and the local interaction between the parts gives rise to a highly (self) organized global structure. Unlike language, however, the city is full of planning, design and attempts to control the city. In fact, each agent operating in the city is a planner/designer at a certain scale (Portugali, 1999, Chap. 11). And yet, due to the size and complexity of the city, none of the many planners/designers operating in it can fully control its final form, structure and evolution.

It should be emphasized that many of the planning and design actions taken in a city – the design and construction of buildings, bridges, roads and the like – require full control and external organization. But as just noted, in the last analysis none of these designs can fully determine the overall structure of the city – not even large-scale urban design projects. From this follows two forms of design: *engineerable design* that is necessary in the design of some of the urban artifacts, versus *self-organized design* that typifies the design of neighborhoods, whole cities and metropolitan areas.

Concluding notes

Our aims in this paper have been, first, to expose the ambivalent relations between design and cognition. Second, to introduce SIRN as an approach to cognition suggesting a perception-action-production view of cognition. Third, to make a start at introducing SIRN as an approach to design. The next step, with which we are currently engaged, is to put these ideas into empirical tests. So far we have done so by means of the *city games* discussed above and by means of computerized urban simulation models. Preliminary results indicate, first, that designers never come to the city tabula rasa. Rather, each comes to, and starts to design in, the city with a *conceptual cognitive map* (cCM) that refers to his/her previous experience in cities. The most prominent cCMs were found to be *mono-centric* and *multi-centric*. Second, the first interaction between the designers and the city gives rise to *specific cognitive maps* (sCM) that are dynamic and change as the structure of the city evolves. It is according to sCMs that the design process proceeds. We have also started to experiment with the two qualitatively distinct design processes noted above – *engineerable* versus *self-organizing design.* However, these and several other experiments and results will have to await further publication.

References

Akin, Omer.1986. *Psychology of architectural design*. London: Pion.

Casakin, Hernan. 1998. “Diagrams, sketches, and the use of analogy in design: experts and novices”. In *Proceedings of the Second International Conference on Thinking with Diagrams 98*, 79-85, edited by P. Olivier. Aberystwyth: The University of Wales Press.

Chomsky, Noam. 1986. *Knowledge of Language*. New York: Praeger.

Cole, M. 1998. *Cultural Psychology*. Cambridge Mass.: Belknap of Harvard University Press.

Do, Ellen, Y. Gross, Mark, D. and Zimring, Craig. 1999. “Drawing and design intentions - an investigation of freehand drawing conventions in design”. In *Design thinking research symposium*, II, 1-9, edited by G. Goldschmidt and T. Porter. Cambridge, MA: MIT Press.

Donald, Merlin. 1991. *Origins of the Modern Mind: three stages in the evolution of culture and cognition*. Cambridge Mass: Harvard University Press.

Edelman, Gerald. 1992. *Bright Air Brilliant Fire: on the Matter of the Mind*. London: Penguin Books.

Dorst, Kees, and Dijkhuis, J. 1995. “Comparing paradigms for describing design activity”. *Design Studies*, 16 (2) : 261-274.

Eckersley, Michael. 1988. “The form of design processes: a protocol analysis study”. *Design Studies*, 9: 86-94.

Ericsson, K. Anders, and Simon, Herbert. 1984/1993. *Protocol analysis: verbal reports as data*. Cambridge MA: MIT Press.

Evans, R. 1989. “Architectural projection”. In *Architecture and its images*, 18-35, edited by E. Blau & E. Kaufman. Montreal, Canadian Centre for Architecture.

Fish, Jonathan. and Scrivener, Stephen. 1990. “Amplifying the mind's eye: sketching and visual cognition”. *Leonardo*, 23: 117-126.

Freeman, Walter, J. 1999. *How Brains Make Up Their Minds*. London: Weidenfeld & Nicolson.

Gardner, Howard. 1987. *The Mind's New Science*. New York: Basic books.

Gibson, James, J. 1979. *The Ecological Approach to Visual Perception*. Boston: Houghton-Mifflin.

Goel, Vinod. 1995. *Sketches of Thought*. Cambridge, MA: MIT Press.

Goldschmidt, Gabriela. 1992. “Serial sketching: visual problem-solving in designing”. *Cybernetics and Systems*, 23:191-219.

Goldschmidt, Gabriela. 1994. “On visual design thinking: the vis kids of architecture”. *Design Studies*, 15(2): 158-174.

Goldschmidt, Gabriela. 1999. “The backtalk of self-generated sketches”. In *Visual and Spatial Reasoning in Design*, 163-184, edited by J. Gero and B. Tversky.

Haken, Hermann and Portugali, Juval. 1996. "Synergetics, inter-representation networks and cognitive maps". In *The construction of cognitive maps*, 45-67, edited by J. Portugali. Dordrecht: Kluwer academic publishers.

Haken, Hermann. 1979. “Pattern formation and pattern recognition - an attempt at a synthesis”. In *Pattern Formation by Dynamical Systems and Pattern Recognition*, 2-13, edited by H. Haken. Berlin: Springer.

Haken, Hermann. 1983. *Synergetics, An Introduction*. Heidelberg: Springer.

Haken, Hermann. 1991. *Synergetic Computers and Cognition*. Heidelberg: Springer.

Haken, Hermann. 1996. *Principles of Brain Functioning*. Heidelberg: Springer.

Haken, Hermann, and Portugali, Juval. 1996. “Synergetics, inter-representation networks and cognitive maps”. In *The construction of cognitive maps*, 45-67, edited by J. Portugali. Dordrecht: Kluwer academic publishers.

Hatna, Erez, Casakin, Hernan, and Portugali, Juval. 2001. “Characterization and classification of cognitive maps: the use of city games”. *Paper presented at the Annual Meeting of the Israeli Geographical Association*, Tel Aviv University, Tel Aviv. December 11-13.

Johnson, Mark. 1987. *The body in the mind: the bodily basis of meaning, imagination, and reason*. Chicago: The University of Chicago Press.

Jones, Christopher. 1980. *Design methods*. N Y: John Wiley & Sons.

Kelso, Scott. 1995. *Dynamic Patterns: the self-organization of brain and behavior*. Cambridge Mass.: The MIT Press.

Lakoff, George. 1987. *Women, Fire and Dangerous Things: what can categories reveal about the mind.* Chicago: The University of Chicago Press.

Lawson, Bryan. 1980. *How designers think*. London : The Architectural Press.

Lawson, Bryan. 1994. *Design in mind*. London: Butterworth-Heinemann Ltd.

Lynch, Kevin. 1960. *The Image of the City*. Cambridge Mass.: The MIT Press.

Miller, George. 1956. “The magic number seven, plus or minus two: some limits on our capacity for processing information” *The Psychological Review*, 63: 81-97.

Newell, Allen, and Simon, Herbert. 1972. *Human problem-solving*. Englewood Cliffs, NJ: Prentice Hall.

Portugali, Juval. (Ed.). 1996a. *The Construction of Cognitive Maps*. Dordrecht: Kluwer Academic Publishers.

Portugali, Juval.1996b. “inter-representation networks and cognitive maps”. In *The construction of cognitive maps,* 11-43, edited by J. Portugali. Dordrecht: Kluwer Academic Publishers.

Portugali, Juval. 1999. *Self-Organization and the city*. Heidelberg: Springer.

Portugali, Juval. 1996b. “Inter-representation networks and cognitive maps”. In *The construction of cognitive maps,* 11-43, edited by J. Portugali. Dordrecht: Kluwer Academic Publishers.

Portugali, Juval. 1997. “Self-organizing cities”. *Futures*, 29:353-380.

Portugali, Juval. 1999. *Self-Organization and the City*. Heidelberg: Springer.

Rossi, Aldo.1986. *The architecture of the city. Cambridge*, MA: MIT Press.

Rumelhart, D.E., P. Smolensky, J.L. McClelland, and G.E. Hinton. 1986. “Schemata and sequential thought processes in PDP models”. In *Parallel Distributed Processing, Explorations in the Microstructure of Cognition*. (2): Psychological and Biological Models, 7-57,edited by J.L . McClelland, D.E. Rumelhart, and the PDP Research Group. Cambridge MA: MIT.

Thelen, Esther. 1995. “Motor development: A new synthesis.” *American Psychologist* 50(2): 79-95.

Schon, Donald. 1983. *The reflective practitioner: How professionals think in action*, NY: Basic Books.

Simon, Herbert. 1979 . *The Sciences of the Artificial.* Cambridge, MA: MIT Press.

Suwa, Masaki, and Tversky, Barbara. 1997. “What do architects and students perceive in their design sketches?: a protocol analysis”. *Design Studies,* 18 : 385-403.

Varela, Francisco, J., Thompson, Evan, and Rosch, Eleanor. 1994. *The Embodied Mind*. Cambridge Mass.: The MIT Press.

Verstijnen, Ilse. 1997. “Sketches of creative discovery”. *Ph.D. dissertation,* Faculty of Architecture Delft University of Technology.

Verstijnen, I., Wagemans, A., Heylighen, A., and Neuckermans, H. 1999. "Sketching, Visual Analogies and Domain-Expertise”. In *Proceedings of 4th Design Thinking Research Symposium: Design Representation*, II.71-II. 77, edited by G. Goldschmidt, and W. Porter. MIT, Cambridge: Massachusetts.

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