A Cognitive Method to Measure Potential Creativity in Designing

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Abstract. Using concepts from creative cognition this paper proposes a cognitive method to measure potential creativity in designing. The empirical data from protocol studies presents examples of the measurement of the novelty, value, and unpredictability in the different cognitive levels. Finally, we propose a model of creativity and designing as situated.

1 CREATIVITY STUDY

Creativity is an elusive concept since it is used to imply various things and abilities. Cooking in a new way could be creative, coming out of a new solution for an old problem is creative, inventing a new physical law is still creative. The ambiguous definitions of the fields and references to creativity used in everyday parlance have enriched the dimensions of creativity studies. Approaches to studying creativity range from cognitive psychology to artificial intelligence [1], [2], [3], [4]. Studies of cognition focus on the internal process of human problem solving using cognitive experiments [3], [5], while others examine historical evidence to explore the life of creative geniuses, who are regarded as creative persons [6]. The study reported here inherits the tradition of cognitive studies of creativity, exploring the intuitive content of the design process and its relationship to creativity in design. Thus, the hands-on experience in designing, including perceptual and conceptual aspects, is proposed as being crucial in generating creative products [7], [8].

One of the important issues in studying creativity is the referential context that indicates the field of evaluation. In cognitive studies and artificial intelligence, researchers deal with mental phenomena or internal mechanisms of creative processes. Other researchers however study creativity in relation to its domain and socio-cultural environments [9] , [10]. The frameworks for studying creativity are defined as consisting of two distinct areas as in Boden's P-creativity and H-creativity and Gardner's small-c and big-c [10], [6].

Referring to Csikszentmihalyi's creativity triangle [11], the focus of this study fits under the psychological/personal level as P-creativity in Boden [10] where personal novelty reconstructs one's conceptual space. This paper however focuses on creativity in a smaller dimension; we study the creativity in a single episode of a design process.

The working definition of creativity in this study includes assessments of novelty, value, and unpredictability. The value here is closely connected to the referential context, which is based on domain knowledge and determines the degree of appreciation for the product. Since this study confines itself to a low level of referential context, the value contributes little to the meaning of creativity so that to avoid confusion and argument this study explore the issue of novelty in the design process first.

This novelty is situated in an episode of a design process. There are various instances of novelty that can be found in the cognitive design process. A designer recognizes new relationship in his sketches that he/she did not find in the first place. A designer invents new semantic meanings for his/her depictions that already have functionality. A designer changes the requirements given by clients or invented by himself/herself. These instances of novelty are unpredictable and this in turn contributes to the possibility of occurrence of creativity in perceptual, functional, and conceptual aspects of the design cognitive activities.

The questions we would like to ask are: what is the novelty in the design process? Can it be the indicator of creativity in design? Is there a method to measure the novelty generated during the process of designing?

2 CREATIVITY IN THE DESIGN PROCESS

The analytical structure of this study principally follows the Geneplore model proposed by Finke, Ward, and Smith [1], which provides a methodological framework for studies of creativity. Two distinct processing components are proposed as fundamental to the general process of creativity. In the *generative* phase, one constructs preinventive structures that could be thought of as initial precursors to the final creative results. In the *exploratory* phase, the properties of preinventive structures are interpreted and modified to generate the creative results. The cyclic process between the generative and exploratory phases is proposed as the process of creative thinking using empirical data from

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visualization, invention, and conceptual synthesis. The phenomena of creative thinking emerge from the interactions among the processes and different kinds of preinventive structures. This paper applies this model in the context of an episode of architectural design, and the preinventive structures of this thinking process as devised in terms of different cognitive levels. According to the Geneplore model, two different types of these preinventive structures should be distinguished. The first kind is in the generative phase as a first response to a design situation. These might be regarded as coming from the knowledge or expertise of the designer. The second kind is the interpretation or transformation of these preinventive structures, which are modified in this exploratory process.

To illustrate, we apply these ideas to Petra's design in Schön and Wiggins [12]. Petra's literal visual appreciation of the marks she drew as 6 units is an example of perceptual preinventive structure in the generative phase, while her apprehension of spatial gestalts of the same marks as three L's is preinventive structure during the exploratory phase. In terms of functional reference of depictions, the "six classroom units" are initial preinventive structure in the generative phase, while the function of "educational way of configuration" is the result of transformation in the exploratory phase.

As a result, several kinds of preinventive structure could be found in this design process. We categorized them according to the analytical structure used in current design cognition research into four cognitive levels [8], [13], [14], [14]. They are physical, perceptual, functional, and conceptual levels. The *physical level* refers to the process having instances related to the external world, comprising drawing, looking, and moving actions. The *perceptual level* refers to the process having instances of attending to visuo-spatial features and relationships in the perceptual mechanism. The *functional level* relates to the process consisting of the instances of functional references mapped between visuo-spatial features/relationship and abstract concepts including meanings and functions. The *conceptual level* refers to the process involving the instances that internally process abstract concepts and process indirect instances from physical and perceptual levels.

The preinventive structures used to study creativity in the design process are visuo-spatial relationship, functional references and goal settings corresponding to the different levels. These types are not exclusive. Other possible kinds of preinventive structures in the design process are not included in the results presented here. The following section describes the methodological issues and the experimental data and procedures.

3 THE METHODOLOGY

This paper uses a case study approach with the data derived from a retrospective protocol study. We followed the process and methods in the series of retrospective protocol of sketches studies produced by Suwa and his colleagues [8], [13], [15]. In this study, the two sets of raw data were obtained from the architectural experiments in Suwa and Tversky [15]

The general procedure of retrospective protocol study involves 1) designing without utterance; 2) reporting with the aid of the videotape that records the designing section; 3) transcribing retrospective utterance into a verbal protocol; and 4) encoding the design process using videotapes, sketches, and protocols. The design process was represented by these media. The protocol was parsed using segmentation and encoded using a coding scheme by two coders including one of the authors. The details of the methodology are omitted here since they have been presented elsewhere [8], [13], [14], [16].

3.1 Segmentation

The entire verbal protocol was divided into small units, *segments*, the definition of which was that one segment accounts for a designer's single intention, and therefore consists of pieces of information that appear to have occurred simultaneously in the designer's mind. New segments could be flagged by thought shifts or change of physical actions, such as depicting so that their lengths ranged from couple words to several sentences. Segments form the basis of this analysis. The following examples of encoded results are illustrated in terms of segments.

3.2 The coding scheme

A *coding scheme* is the collection of the codes used to represent the design process for the analysis. It is postulated as a representational system to describe, understand, explain, and even predict the cognitive activities of designing

The coding scheme we utilized was established by Suwa, Purcell, and Gero [13]. It has been applied by the authors in a series of experiments [16], [17], [18], [14]. It consists of the four cognitive levels that have been described earlier. We named it the design content-oriented coding scheme, in short DCOCS.

3.3 Instances

The *instance* in DCOCS refers to an observed occurrence of a specific activity in a level. For example there are: drawing instance (D-instance) and looking instance (L-instance) in the physical level. An instance of perceiving visuo-spatial relationship is a P-instance in the perceptual level; an instance of attaching a function-reference is an F-instance in the functional level; and an instance of goalsetting is a G-instance in the conceptual. Each level in a segment might have more than one instances or no instance at all, depending on the observed data. The order of the levels was physical, perceptual, functional, and conceptual from the lowest to the highest. The higher-level instances might have dependencies on lower-level instances; for example, an F-instance might depend on a P-instance and a D-instance.

3.4 Index

An *index* was given to show the occurrence of the instance in the physical, perceptual, and functional levels. A *new* index indicated the initial occurrence of an instance in the design process observed, and an *old* index indicated its following occurrences. This index plays an important role in observing the shift from generative phase to explorative phase, and indicated the transformation of the preinventive structure of an instance.

Using the concepts of segmentation, coding scheme, and index, the design process observed was transformed into a series of information matrices. Figure 1 is one of the encoded segments. It consists of the transcript and four cognitive levels. The perceptual level has a P-instance, Pfp, with a new index, and it dependant on a D-instance, Dtd, with an old index in the physical level. The naming of different kinds of instances can be found in Tang and Gero [16].


Transcript

First, I was drawing over the site line to see what kind of form the site line is.

D_TYPE		INDEX	BASEON	L_TYPE	L_CONTENT
Dtd	1	old	L1	L1	green

P_TYPE		INDEX	P_CONTENT	INDEX	BASEON
Pfp	1	new	site line	old	Dtd1

F_TYPE	INDEX	F_CONTENT	INDEX	BASEON

G-TYPE		F_CONTENT	TRIGGER
Type1.2	-1	to see the form of site line	[illegible]

Figure 1. An example of an encoded segment

In the following sections, we examine our encoded protocol for the instances in different phases to understand the design process from the point of view of creative cognition.

4. OBSERVING CREATIVITY IN THE DESIGN PROCESS

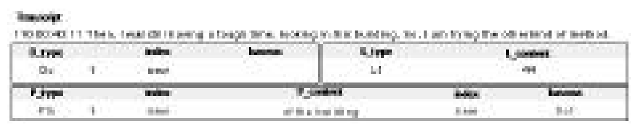
The concept of creative cognition provides a new viewpoint in the understanding of the creativity in the design process as described in the encoded results. The essential component of the Geneplore model is the preinventive structure. It might be created and utilized without further modification in a generative phase, or could be transformed to form a new opportunity in an exploratory phase. The token to identify the shift of phase is the index.

The Geneplore model proposes that the cyclic shift between generation and exploration occurs when people engage in creative thinking. In the same vein, finding more preinventive structures in the exploratory phases of designing implies that the design process tends to be creative. The ratio of preinventive structure in exploratory phase to generative phase therefore could be regarded as the beginnings of a measure of the creativity in designing. The encoded segments are used to illustrate how we can observe this creativity in our empirical data.

4.1 Identifying preinventive structure

The preinventive structures we identified from the design process are perceptual instances, functional instances, and goal-setting instances. They possess the preinventive properties, being novel, ambiguous, meaningful, emergent, incongruous, and divergent.

A P-instance as preinventive structure in the perceptual level was the perceiving of visuo-spatial relationship as the shape of building from his depictions in our example, illustrated by Pfn in Figure 2. This was similar to the object form that is one of the preinventive structures proposed by Finke, Ward and Smith [1]. This P-instance was novel and perceived from new depictions. It had not been transformed so that we could identify it as preinventive structure in a generative phase.


Transcript

D_type		index	baseon	L_type	L_content
[illegible]	1	new		L1	[illegible]

P_type		index	P_content	index	baseon
[illegible]	1	[illegible]	of the building	[illegible]	[illegible]

Figure 2. A P-instance as preinventive structure in a generative phase

A functional reference as preinventive structure in an F-instance was the attaching of functional reference to P-instances or D-instances. For example, the designer attached the functional reference of "building" in the emerged shape he perceived in the sketches, illustrated by Fnp in Figure 3. Here both the F-instance and P-instance were novel so we could identify the functional reference as being in the generative phase.

A preinventive structure in a G-instance was the goalsetting based on initial requirements, explicit design knowledge, or tacit intuition. In this example, the Type1.1 goalsetting was triggered by new F-instances and new P-instances. The designer set up the goal to place the building when seeing the building and attaching the meaning to the shape. The indexes of these instances enabled us to identify the goalsetting as being in the generative phase. We further identified preinventive structure in an exploratory phase following the P-instance, F-instance, and G-instance. We found that this kind of preinventive structure has been emphasized in several different design studies.

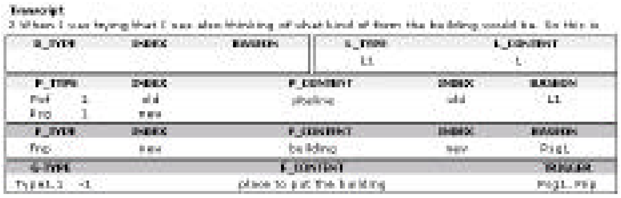


Figure 3. A functional reference and a goalsetting as preinventive structure in a generative phase.

Preinventive structure in the perceptual exploratory phase refers to perceiving a new visuo-spatial relationship in an existing depiction. For example, the designer perceived the symmetry in the existing depictions, illustrated by the Prp in Figure 4. A new visual attribute was found in the original visual pattern or form through the designer's exploration. This was called unexpected discoveries in previous design literature [12], [19].

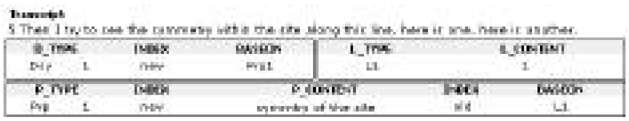


Figure 4. A P-instance as preinventive structure in a explorative phase

In the same vein, attaching a new functional reference to old P-instances or D-instances was identified as preinventive structure in the exploratory phase. For example, the designer gave a new meaning of "circulation within the site" to the old spatial relationship in the sketches, illustrated by the Frei in Figure 5. This was called re-interpretation in previous literature [19] and later formed the basis of situated- or s-invention [8].

Figure 5. A F-instance as preinventive structure in a explorative phase

The goalsetting that was extended from a previous G-instance was identified as preinventive structure in the exploratory phase. For example, the designer gave more requirements for the coffee shop; except basic functions he wanted the coffee shop have a special relationship, illustrated by Type1.3 in Figure 6. This G-instance might be caused by broadening or narrowing goals or by solving a problem caused by previous goalsetting. With the above method of identification, we examined the encoded protocol under the assumptions of creative cognition. The results are presented in the following section.

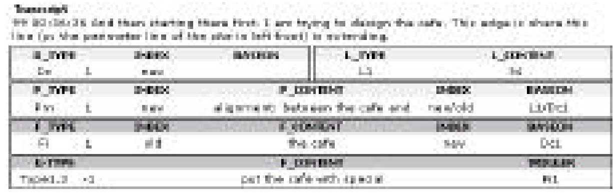


Figure 6. A G-instance as preinventive structure in a explorative phase

4.2 Identifying the shifts between generative and exploratory phases.

The two sets of data we analyzed were the architectural design processes of a novice and an expert. After encoding the protocol using DCOCS, we calculated the numbers of preinventive structures in the generative and exploratory phases for both subjects. The distributions of preinventive structures in different levels demonstrate different characteristics between the expert's design process and the novice's.

For the novice, more than 70% of preinventive structure in all levels was in the generative phase, Table 1. In the functional level, the preinventive structure in generative phases even exceeded those in exploratory phases by 70 %.

Table 1. The frequencies of preinventive structures of the novice in terms of different levels

	Generative phase	Exploratory phase
Perceptual	78.5 %	21.5 %
Functional	85.3 %	14.7 %
Conceptual	71.8 %	28.2 %

In the expert's data, over 75 % of the perceptual preinventive structures were in the explorative phases, Table 2, and more than one quarter of the other kinds of preinventive structure were in the explorative phases.

Table 2. The frequencies of preinventive structures of the expert in terms of different levels

	Generative phase	Explorative phase
Perceptual	24.8 %	75.2 %
Functional	75.4 %	24.6 %
Conceptual	65.8 %	34.2 %

It is noteworthy that the ratios of preinventive structure in the exploratory phases to generative phases in the expert's data exceeded that in the novice's in all levels.

Finally, we grouped the instances with both kinds of preinventive structures against the instances without novelty involved in three different levels. The results showed that almost 70 % of perceptual and conceptual instances produced novelty, Table 3, and that the distribution between the novice and the expert were similar (***p***-Value < 0.40).

Table 3. The percentage of instances with preinventive structures

	Novice	Expert
Perceptual	71.5%	67.0%
Functional	30.0%	39.9%
Conceptual	70.3%	64.0%

To sum up, both the design process of the novice and the expert demonstrated generating novelty in perceptual and conceptual in almost 70% of instances. On average, about 20% of preinventive structures in the novice's process were transformed into the explorative phase, while about 44% of preinventive structures in the expert's process were transformed into the explorative phase.

Some limitations of the empirical analysis have to be drawn here. First, the results are generated from a single case study. Second, it might not be appropriate to include functional instances as the reference to calculate the preinventive structures because their properties in this context were similar to the physical actions.

4.3 Measuring the creativity in the design process

The assessments of novelty, value, and unpredictability were utilized to measure the creativity in the design process. The first criterion was assessed using preinventive structures in the Geneplore model [1]. This framework is proposed to describe basic cognitive processes related to creativity. We identified its fundamental structures to assess the novelty in the design process. Instances with preinventive structures indicate the novelty generated in the design process no matter which levels it occurs. It could be a new visuo-spatial relationship, functional reference, or goalsetting. The novelty emerged in the design process does not guarantee a creative design process rather the potential to be. Our data showed both novice and experts generated a similar level of novelty in the design process, Table 3. What we evaluated here related to the rate of not repeating in different cognitive levels during a design process. For instance, a designer might keep perceiving the same images in the design, neglecting the new possibility hidden in sketches. In our data, these two designers perceived at similar rates new visuo-spatial relationships during their design process, and around 70% of these relationships were novel in the process.

To assess value and unpredictability, we utilized the indexes of instances incorporating with the concept of shifts between the generative and explorative phases in the Geneplore model. It is proposed that the cycles between the phases of generation and exploration typically increase the possibility of being creative. By continuing these cycles, one would gradually focus the emergent structures on particular themes and explore their possibilities. In terms of our working definition of creativity, the underlying assumption is that the value and unpredictability increases when these cyclic shifts occurs. The ratio of the number of preinventive structures in explorative phases to total number of preinventive structure, therefore, could be used as a measurement of the possibility of creativity.

Based on this notion, we postulate that the process of the expert was more creative because the value and unpredictability in his design was richer than the novice. Comparing data in Table 1 and Table 2, the expert produced more preinventive structure in explorative phases on perceptual, functional, and conceptual levels by 53.7, 9.9 and 6 percents According to the Geneplore shift, the expert had a higher production of value and unexpectedness in these cognitive levels than the novice.

What we evaluated here could be regarded as the transformation of design knowledge including perception-based and meaning-based knowledge. Every preinventive structure in an explorative phase could be treated as a refined version of previous preinventive structure in a generative phase. The latter principally results from designers' expertise. How to read some visuo-spatial relationship, how to utilize sketches by attaching meanings, and how to reason about design problems are all part of design knowledge. The shift of preinventive structure from generative phase to explorative phase represented the restructure or modification of existing knowledge. This in turn can contribute to the generation of creativity.

Moreover, the expert discovered significantly more emergence in the perceptual level. This measurement could be further used to indicate the designer's creative abilities in different cognitive levels. Some designers might be good at perceiving emergent visuo-spatial relationships and transforming them as the impetus of new aesthetic forms, while some might be good at reformulating conceptual goals to solve problems in a creative way. In our case, the expert's perceptual creative ability largely increased his possibility of creativity.

During the analysis, this study did not distinguish the creativity in the process and the creativity in the end products because of the lack of referential context in this study. In the level of an episode of a design process, a creative process most likely leads to a creative result since the evaluation is singular and simple. To examine the analytical results, we observed their design results. It was clear that the expert's museum design was interesting and thoughtful regarding to the buildings, circulation, feelings, and interactions between the museum and users. In contrast, the novice's design was straightforward and simple. From their sketches shown in Figures 7 and 8, we could recognize that the expert's sketches had the potential to promote more perceptual novelty and increase the possibility of creativity. In terms of conceptually requirements fulfillment and problem formulation, the expert exhibited innovative ideas to enrich the environmental interactions and at the same time fulfill the requirements of a good museum. It was a strong comparison between a more-than-ten-year experienced designer and an about to-graduate novice designer. The design sketches and results clearly showed the dramatic difference, and more importantly our proposed measurement demonstrated the differences as well.

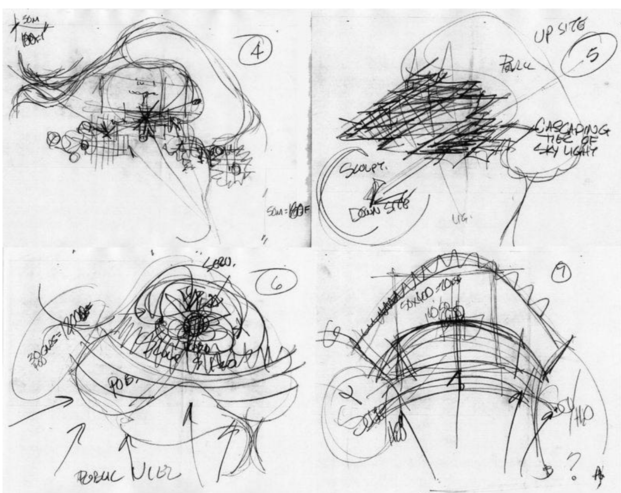


Figure 7. The expert's sketches number 4, 5, 6, and 7

5. DISCUSSION

This paper has proposed a cognitive approach to studying creativity in designing. For creative cognition, the context of design could stimulate the discovery of different types of preinventive structure, and enable researchers to incorporate natural, realistic, and ecological conditions. These have been proposed as important direction in creative cognition. The research results in creativity in design have the potential to enrich the field and understanding of creative cognition.

In terms of design studies, we have more empirical and quantitative methods to study creativity from a creative cognition viewpoint. The methods to increase creativity in creative cognition would provide interesting implications in design. For example, designers could directly utilize the concepts of generative and exploratory phases in the design process. Their related applications have been proposed in producing creative results in mental synthesis, so this method might be useful in creative design. The implications of this cognitive method to measure potential creativity in designing are discussed further in terms of creativity model and situated cognition.

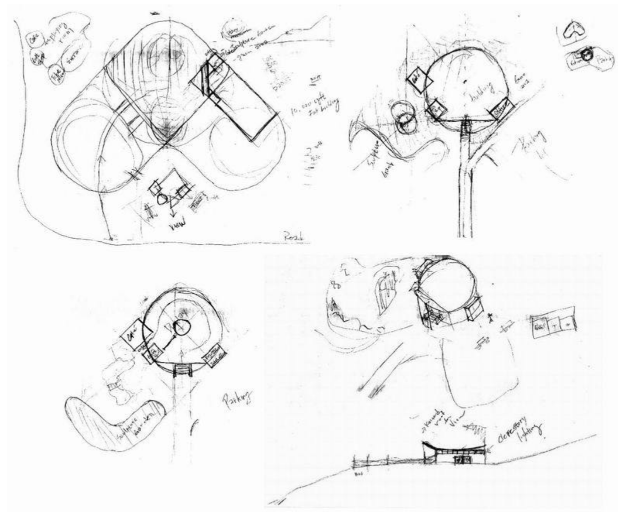


Figure 8. The novice's sketches number 1, 2, 3, and 4

5.1 The system model of creativity

The events measured in this study were the cognitive behaviors of designers in a design process, rather than the process itself, for example, sketching, attaching functional references and reasoning the problems. The accumulation of these local cognitive events results in the outcome of the process. It could be creative in a sense that the outcome is novel, valuable, and unpredictable during the episode of design process. Creativity, as a result, does not solely happen inside people's cognitive behaviors.

It happens quite often that a designer regards his design as creative and then found out that nobody recognizes this. This is because of the existence of referential context. To describe the effect of referential context, Csikszentmihalyi [11] proposed a system model of three components, which describe where the creativity exists. *Domain* consists a set of symbolic knowledge and procedures shared by a particular society; *Field* includes a group of people who evaluate, select, and preserve a new idea or product for the domain as gatekeepers; *Person* is responsible for creating the idea or product which might change the field and even domain. This perspective is concordant with the relative creativity proposed by Christiaans [20]. Creativity therefore is situated in relation to its context, including personal, field, and domain aspects.

This study introduces a new level under the person area. We examined the behaviors of a single design process through the notion of creative cognition. It is proposed that the aggregation of all the cognitive events results in the outcome of this design process, and this outcome produces an impetus for creativity in person level.

In terms of our analytical structure, the novelty and value of preinventive structures found in the generative phases may be new and unpredictable in this design process; however, it could be old and existing in terms of this designer's experience because these preinventive structures could be regarded as expertise generated from experience. On the other hand, the novelty and value of preinventive structures found in the explorative phase more likely generate creativity in terms of personal-level creativity since they are different from conventional responses. It does not however guarantee the results from the design process will be regarded as creative because it heavily depended on external referential context.

The model of creativity could be represented in a four-element square shown in Figure 9. The spectrum of time and the evaluation group for creativity should include the process level. There are interactions between these four areas, for example, the design canon in the domain affects the design process of individual designers. The concept of creativity generates from the inter-relations among these four areas.

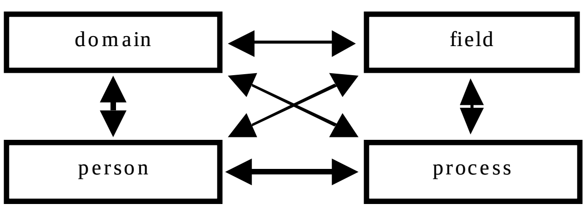


Figure 9. The model of creativity that takes account of the individual design process

The process stands for the phenomenon we measured in the preinventive structures and shifts between generative and explorative phases. Any new ideas generated in the process level have to be evaluated and tested through the rest of areas.

5.2 Conceptual designing as situated

Using our analytical structure, the design process could be regarded as composed by different instances in four cognitive levels and their inter-relationships. Instances with preinventive structures occupy a large percentage of the design process. This indicates one of the features of the design process, novelty. It essentially comes from the explorative phase. New transformations of preinventive structures could be triggered by both new and old structures of the same or different kinds. It seems to be reasonable to describe the design process as opportunistic because each single cognitive instance might have the potential to evoke novelty in the design.

Schön and Wiggins [12] have described this phenomenon as "reflection-in-action" in their design theory. The design process is controlled and driven locally. The concept of indices in our analysis further describes this idea. Physical instances, drawing and seeing, were the main media for different instances to occur. By seeing them, designers found new visuo-spatial relationship and functional references. Generally, very few instances occur without relations to other instances in lower levels. These form the situation for different cognitive events to occur. Without them, the transformations of preinventive structures could not happen, just like designers cannot perceive new possibilities of spatial configurations without seeing existing depictions. These existing depictions, spatial relationship, and functional references establish a local situation stimulating a designer's perception and conception to generate creativity.

The concept of confronting design situation proposed here is essentially inspired by *situated cognition* in Clancy [21]. This perspective emphasizes the relationship between cognitive events and their current context. In this case study, we could see that the design process advances and changes in response to the local cognitive events. A transformation of a perceptual instance might end up with the generation of a new concept. Gero [22] pointed out that "where you are when you do what you do matters", describing conceptual designing as a sequence of situated acts to response the assumption in design studies. This study provides some empirical data for describing designing as situated in local cognitive events.

Finally, this study should be regarded as an attempt to probe the measurement of possibility of creativity in design process. All the results and methods were based on cognitive behaviors of human designers. However, it would be interesting to apply these structures in computational creative systems, such as separation between generation and exploration or preinventive structures in different levels. These future studies could tell us more about creative systems of both cognition and computing.

Acknowledgements

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