Inter-linkages in the design process: a holistic view towards design knowledge and sketches

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Abstract

This paper reveals the close connection between design knowledge and sketches in an attempt to propose a holistic view of design studies. Two sets of experimental protocol data were analyzed. We first observed the interaction between meaning-based design knowledge and sketches in our residential house design project. The protocol collected in a museum design was analyzed using design content-oriented coding scheme to show detailed linkages between perception-based and meaning-based knowledge and sketches. The results demonstrate a close link between design knowledge and sketches. The dichotomy of design knowledge was proposed to pinpoint the importance of design media, such as sketches in this study. As a result, the design process should be studied from the combination of design knowledge and sketches.

Inter-linkages in the design process: a holistic view towards design knowledge and sketches

Design sketches and design knowledge are amongst the most important issues of design research. There have been significant findings regarding these two aspects (Gero & Rosenman 1990; Goldschmidt 1991; Suwa and Tversky 1997; Purcell and Gero 1998; Heylighen, et al. 1999; Uluoglu 2000; Varejão, et al. 2000; Goldschmidt 2001). The emerging problem of design research is failing to connect these results to form a holistic view of the roles of sketches and knowledge in design. Design knowledge includes the perceptual recognition and discovery of interesting visuo-spatial features and consolidation of ideas presented on paper. Similarly, design sketches require design knowledge to form an understandable presentation and to read the conceptual meanings revealed by drawings. This study intends to explore the inter-linkages between design knowledge and design sketches through cognitive behaviors of designers.

Design knowledge and sketches

The knowledge used in designing can be distinguished using various types of categorizations. The recent researches tend to include every aspect of the design process into the framework of design knowledge. For example, the recent computational model of design knowledge (Varejão, et al. 2000) proposed an ontological framework for knowledge-based design systems. This structure included design requirements and artifact descriptions. This structure also included five major design activities that are applied to manipulate knowledge and to generate end products. A similar structure of design prototypes has been proposed in design studies to identify the different aspects of design knowledge in terms of function-behavior-structure (Gero 1990).

There seem to be two distinct kinds of design knowledge. One is the normative description of a knowledge body and its attributes describing the content of a design unit, for example, the components of a living room. The consensus of the content of a design unit among designers and clients establishes the foundation of communication. The extra personal interpretation of a design unit, however, differentiates a designer from the others. The other kind of design knowledge is the relationship between these design units and their attributes describing the knowledge designers use to reason the design problems, to realize the solutions, and to progress the design process. For example, how to establish a proper circulation connecting a garage and a living room may both produce and resolve the problem of a pathway in a house.

This concept of dichotomy has been defined as declarative and procedure knowledge of meaning-based representations in cognitive psychology. The former includes all explicit knowledge of various facts of the world, while the latter includes how to perform various tasks based on declarative knowledge. Anderson (2000) proposed detailed structures of them as propositional networks and schemas.

The sketches studied in this paper refer to depictions made by pens on papers. The content of our exploration includes the cognitive activities that are related to sketches. They are drawing sketches, looking/revising sketches, and perceiving visuo-spatial relationships in sketches. In a sense, we try to explore the interactions between design knowledge and “sketching” that includes physical depictions and cognitive events of designers.

Two sets of data were analyzed from our research project and from Suwa’s (Suwa and Tversky 1997; Tang 2002). The data of Suwa’s project contained encoded protocols of one expert and one novice architects participating in a museum design. The details of this have been published (Tang and Gero 2001a; Tang and Gero 2001b; Tang and Gero 2001c; Tang and Gero 2001d). The data of

our research project contained a collection of protocol and videotapes of 5 experts and 5 novices participating in a residential house design (Tang 2002). The 5 experts had more than 25 years of experience in residential house design. We observed the general features of design knowledge and sketches in these 12 data sets, and analyzed further the detailed relationship between design knowledge and sketches using encoded protocol.

Observing design knowledge

We first observe the design knowledge and sketches following the dichotomy of declarative and procedural knowledge. In terms of declarative knowledge, our observation found that the experts produced more complete lists of requirements in regards to the same design brief than the novices did. Although both briefs in the residential house and the museum design provided detailed functional requirements, these experts still produced their own checklists regarding different aspects of the design. The issues concerning the experts in the experiments were much richer than those outlined in the design brief and those concerning the novice designers. For example, the concern about building materials and council restrictions were important in the experts' design processes of museum, but not so in the novices' processes. This implies that the knowledge body of a design unit, a residential house or a museum, in architectural experts consists of more detailed attributes and these then enable experts to produce more thorough solutions regarding different aspects.

In the residential house design setting, we inadvertently omitted the specific requirement for a second toilet. During the experiments, none of the novice designers detected this problem in their designing processes. All experts however detected the lack of the toilet in the requirements and expressed concern about it within the experimental duration. It is possible that novices would have found out this missing requirement if given more time. This situation demonstrates one of the well-known differences between novice and experts. The efficiency of experts implies that they are more familiar with the attributes of the knowledge body than novices.

Design sketches play a role as detection aids in these situations. These experts detected the missing requirement when scanning through their sketches. Sketches serve not only as an external memory aid, but we speculate that the spatial configuration of the residential house reveal the missing features. The mismatch between spatial configuration and the attributes of a residential house enables them to discover the missing requirements.

In terms of procedural knowledge, we found that the experts had more organized and longer scripts to advance the design process. In residential design, experts took care of different aspects of the design in clear order, while in museum design the experts explored the unknown issue of the museum in a systematic way.

All of the experts controlled the design process more effectively than the novices did. In the experiments of residential houses, all the experts finished the design with scaled details within 45 minutes. These results imply that the procedural knowledge experts possessed enabled them to cope with design problems more effectively and efficiently. One very experienced designer in residential design appeared to simply describe the design on the papers without ostensive thinking. We could speculate that he utilized his declarative and procedural knowledge without hindrance in solving this problem, which he had been doing for the past 25 years. The design quality however was obviously better than the novices.

Different experts however had different ways to approach design. For instance, some preferred to draw bubble diagrams and reason about the requirements, alternatively following the design methods, while one expert, being also a senior lecturer of design, preferred to list all the requirements on the right side of the papers first, Figure 1. After reasoning the requirements, he

started to draw corresponding drawings on left side of the papers next to the requirements. These could be regarded as personalized aspects of procedural knowledge, which were established corresponding to their personal capacities and experience.

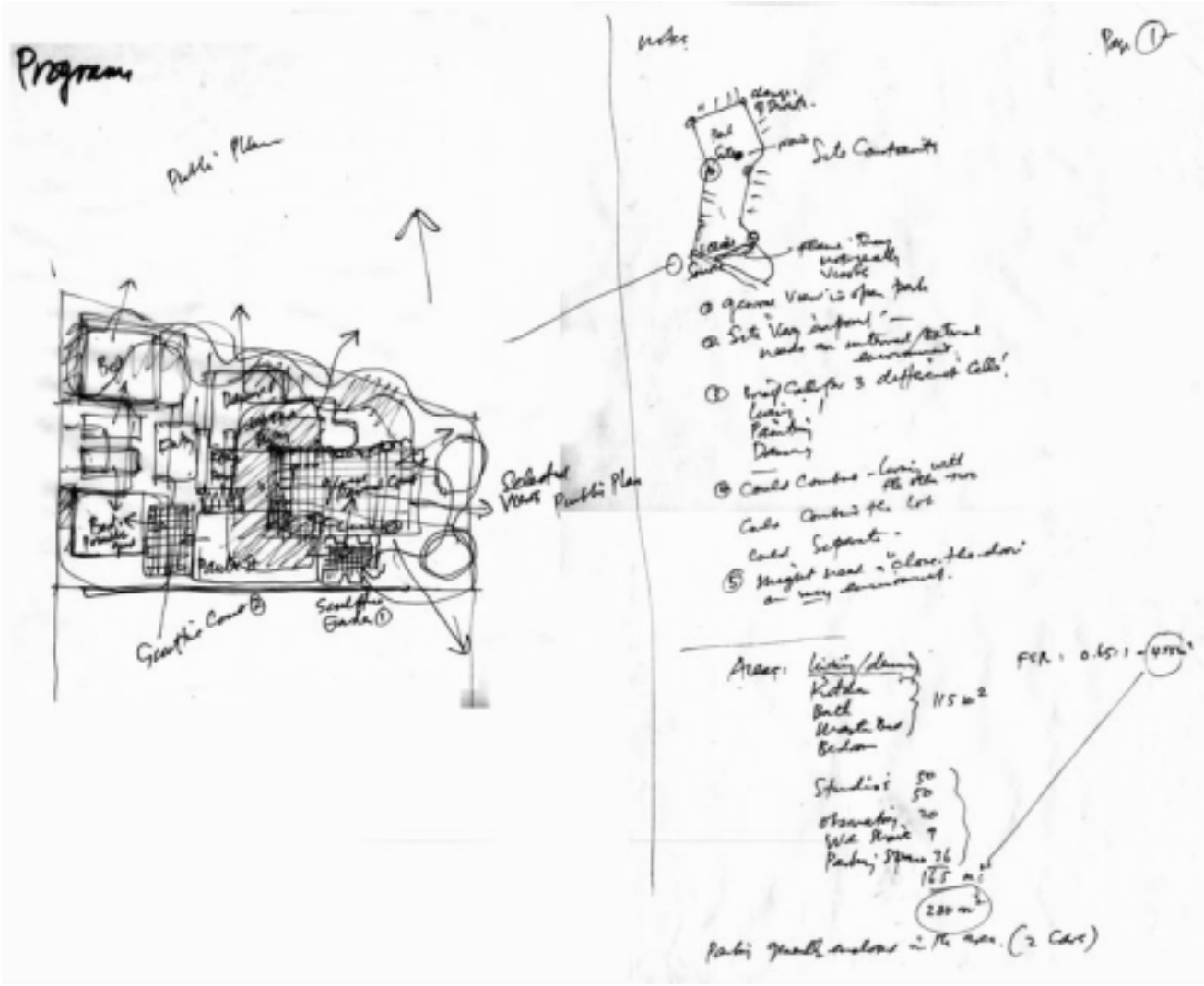

Figure 1: A sketch of the expert architect who wrote requirements first on the right side and then drew ideas on the left side.

The efficiency of procedural knowledge of experts includes their utilization of sketches. The experts in residential house design tended to draw firmly and carry on the progress without trial and error in sketches. In the novices' sketches, modifications and even erasure could be observed frequently. The very experienced designer in residential design who appeared to simply put his design on papers produce the final design in 20 minutes, Figure 2. The quality was however satisfactory. We speculate that his rich procedural knowledge of utilizing sketches enables him to map the conceptual requirements and visual configuration on papers precisely. The interaction between requirements and visuo-spatial properties then further shape his knowledge. The expert in the museum design did not possess such rich knowledge of museum design, so his design was not as precise as the sketches we saw in the residential house design, Figure 3. If given 10 years experiences in museum design, his sketches might look as precious as these in residential design with the aid of his knowledge in mapping functions and forms in terms of museum design.

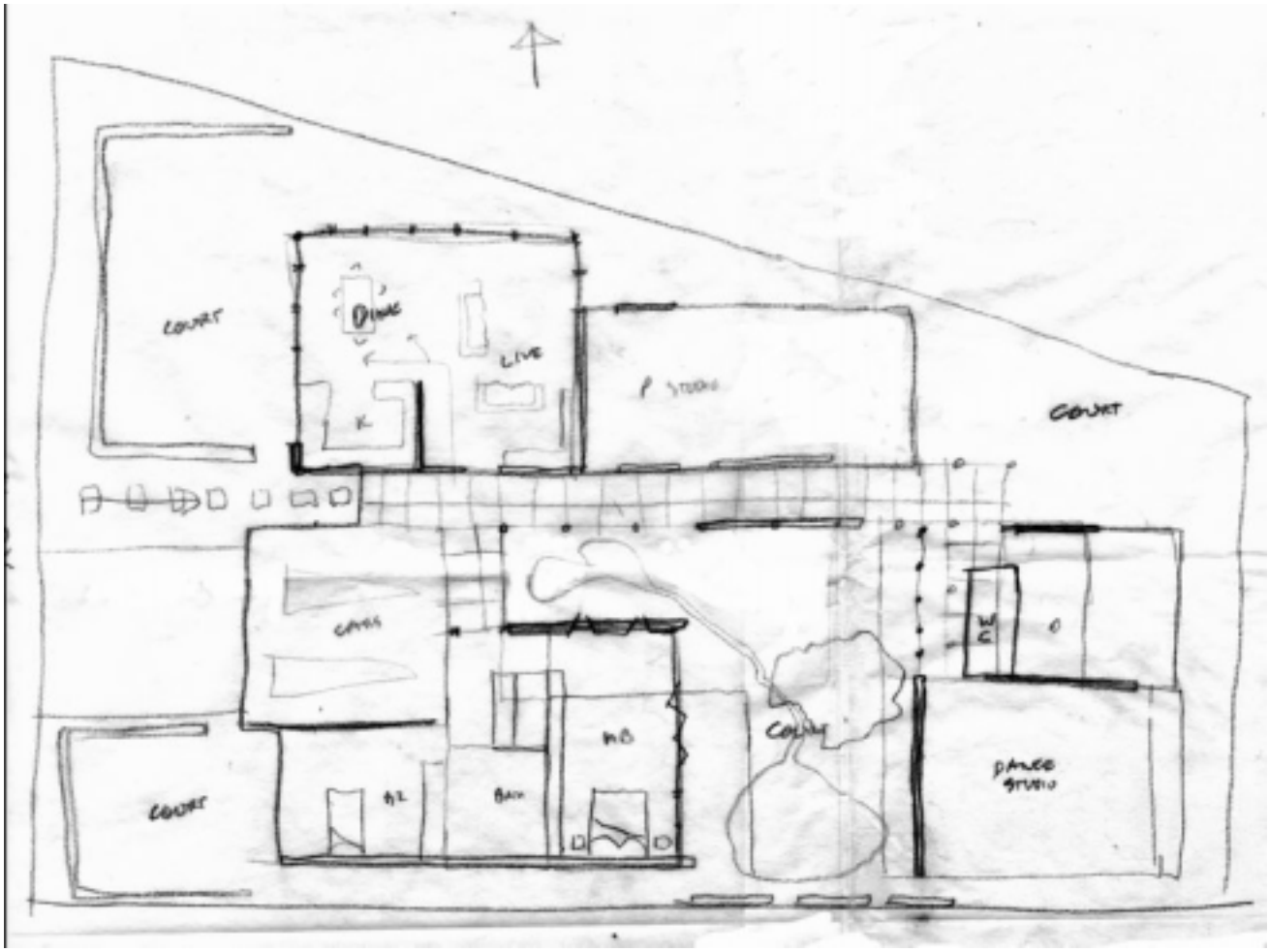

Figure 2: The design produced by the very experienced designer in residential design who appeared to simply put his design on papers.

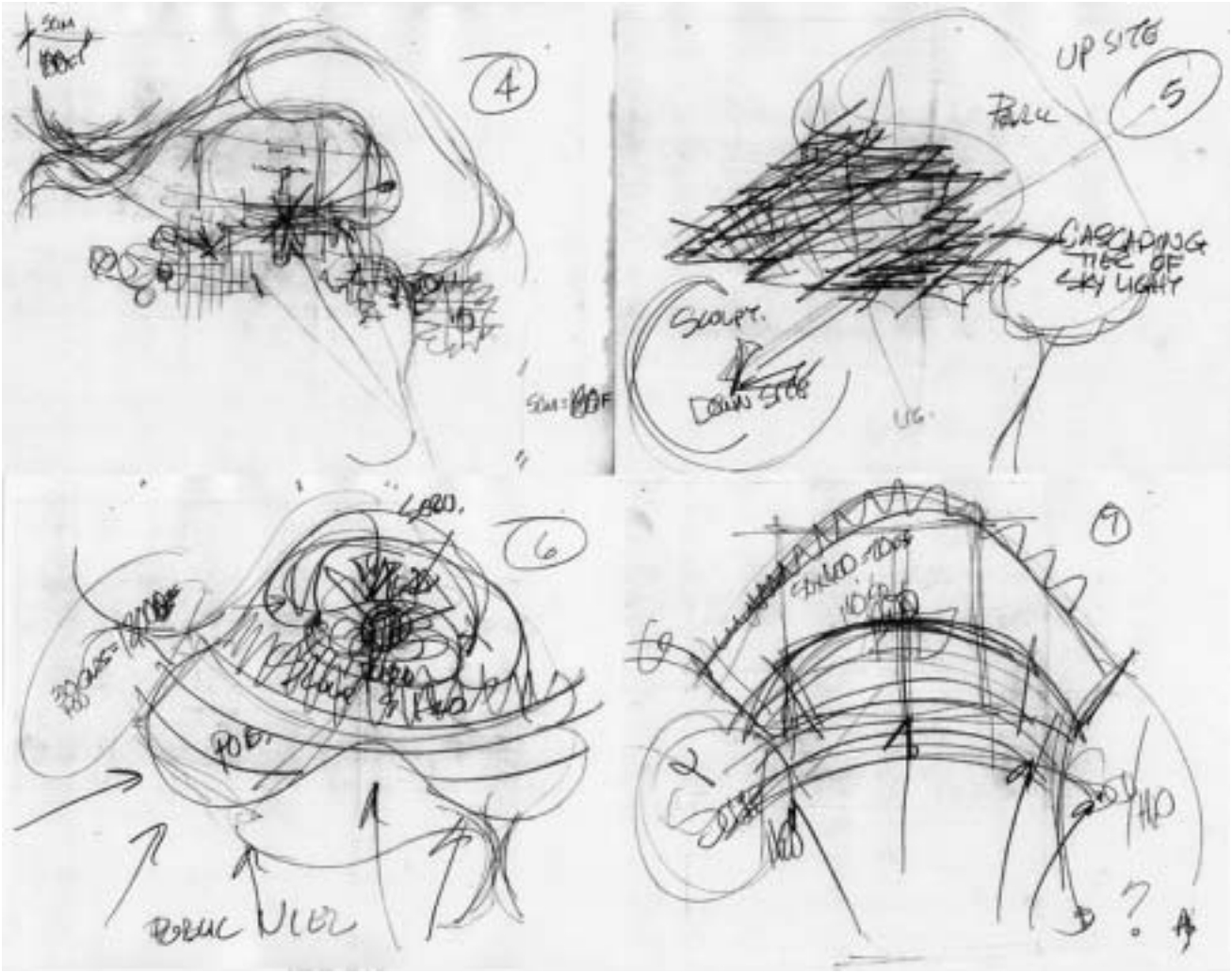

Figure 3: The number 4, 5, 6, 7 sketches produced by the expert in the museum design.

These observations reveal a close interactive connection between design sketches and knowledge. To explore the details further, we investigated the linkages between knowledge and sketches using protocol analysis. The relationship among sketches and design activities in different cognitive levels are examined in our encoded protocol. In the following, we first describe our method and then present the analytical results.

Observing the interlink between design knowledge and sketches

This study applied retrospective protocol analysis in the following study (Ericsson and Simon 1993). The subjects were an expert and a novice architect participating in a museum without interference. After design sessions, they gave protocols with the aid of videotapes documenting their design processes. The protocols data were segmented and analyzed by design content-oriented coding scheme (DCOCS) devised by Suwa and his colleagues (Suwa and Tversky 1997; Suwa, Purcell et al. 1998; Suwa, Gero et al. 2000). Each segment in the design process was categorized through four cognitive levels, physical, perceptual, functional, and conceptual. There were dependencies hidden in these levels, for example, a perceptual seeing instance depended on a physical drawing instance. These dependencies established the perpendicular linkages in specific time duration, a segment. The foci of our exploration are these linkages. They reveal the relationship between design knowledge and sketches. In the encoding process, two coders participated. Details of these encoded data have been published (Tang and Gero 2000; Tang and Gero 2001). To clarify the terminology, the instance in DCOCS refers to an observed occurrence of a specific activity in a level; for example, depicting a line is a drawing instance (D-instance) in the

physical level. An instance describes an occurrence of an event. It could be drawing, looking, perceiving, and functional referencing, in short L-instance, P-instance, and F-instance.

In the previous discussion, we focus on knowledge of meaning-based representation according to Anderson (2000). Meaning-based representations attempt to conceptualize some significant aspects of an experience. Another comparable kind of knowledge Anderson proposed is knowledge of perception-based representation that attempts to preserve much of the structure of a perceptual experience. In the design research community, perception-based representation has not received much attention as one kind of knowledge. We however suspect that the perception-based knowledge makes the design process different from pure scientific rational activities. Designers have to reflectively interact with media that could be sketches, short-term memory, or computer-mediated material. Perception-based knowledge is the channel for the communication between designers and media.

The concept of different representations proposed by Anderson (2000) therefore was applied to analyze our encoded protocol. They consist of perception-associated instances and function-bounded instances. The perception-association instances could be the bases for perception-based representation, with the function-bounded being the bases for meaning-based representation. For example, the connection between a depiction and its corresponding visuo-spatial relationship could be stored as knowledge of perception-based representation. Similarly, the semantic connection between a depiction and its corresponding functional reference could be preserved as knowledge of meaning-based representation.

Knowledge of perception-based representation

These perception-associated instances referred to making different kinds of depictions, looking at existing depictions that are drawn in previous segments, and attending to visual features and visuo-spatial relationship through existing depictions.

The identification of perception-associated instances was done by checking whether an instance had either direct or indirect associations with a visuo-spatial relationship. A direct perception-associated instance meant that this instance was perceived as part of a visuo-spatial relationship. We identified the relationship from video images and protocols. For example, the designer reported “Then I try to see the symmetry within the site along this line, here is one, here is another..”, and, at the same time we saw that he drew a line in the middle of the site. We recounted consequently that the site and the line were perceived as parts of the symmetry, and thus these D-instances were perception-associated. An indirect perception-associated instance was a source instance perceived by a P-instance, the first, which was included within another P-instance, the second. This source instance therefore had one direct perception-association from the first P-instance, and at the same time had one indirect perception-association from the second P-instance.

The numbers of perception-associated and non-perception-associated instances of both participating designers were calculated. The results indicated that more than 60% of the D-instances were perception-associated, while 80% of L-instances were perception-associated, Table 1. There were about 15% of P-instances being perception-associated. These experts had more perception-associated instances than the novices in terms of D-, L-, and P-instances.

Percentage (%)	Novice (SM01)		Expert (EM01)	
	Perception-associated	Non-perception-associated	Perception-associated	Non-perception-associated
Drawing instance	59.0	41.0	71.1	28.9
Looking instance	79.8	20.2	88.6	11.4
Perceptual instance	14.9	85.1	17.0	83.0

Table 1: The percentages of perception-associated and non-perception-associated instances of the novice and the expert architects.

The linkages between sketches and different cognitive actions, including drawing, looking, and perceiving, are the structure of a perceptual experience in Anderson's definition of perception-associated representation. They are design knowledge applied in the design process if these linkages are retrieved from designers' mind, or they are design knowledge learnt during the design process if these linkages are created in the new situation. The non-perception-associated D- and L-instances represent the doodles and revising that are pure external representation without reflection to the designers' attentions yet.

The results indicate that this expert had better abilities in utilizing the sketches because more than 70% of drawing and looking actions were utilized in this perception. This implies that this expert had better knowledge to master the media and to provoke more opportunity in sketches. These linkages are knowledge of perception-based representation, and this connection in the design process is evident. Designers learn perception-based knowledge to use media in design processes, and in turn apply it to facilitate the progress of design.

Knowledge of meaning-based representation

We examined further the relationship amongst D-, L-, P-, F- instances to explore knowledge of meaning-based representation. D-, L-, P-instances are related to the media that designers use to reflect their thoughts and ideas. Some of them were arbitrary without conceptual intentions and meanings, such as purposeless doodling on papers, but some were given meaning through designers' intentions. One square might represent a garage in a residential house, and an emergent space between two circles could represent the tension between two buildings. In our analytical structure, the linkage between D-instance and F-instance and the linkage between P-instance and F-instance respectively represents these two situations.

The method to identify a function-bounded instance was checking whether an instance had either direct or indirect functional references in a segment. A direct function-bounded D-instance meant that a designer knew the functional reference of a depiction when it was created. For example, in a segment a designer reported "*First, I tried to place the building over here, so you enter here, you see all the things and finally come to the building.*", and, concurrently in the video, we saw that he drew a square inside a big circle. We consequently recounted that he has attached a functional reference to the square, and thus this D-instance of drawing a square was function-bounded.

In contrast, an indirect functional reference was one in which a designer attaches meanings to a D-instance through L-instances or P-instances. In the first case, the L-instance had a direct functional reference and the D-instance has an indirect functional reference. In the second case, the P-instance had a direct functional reference and the D-instance had an indirect functional reference and a direct perception-association.

The results indicated that more than 55% of the instances were function-bounded, Table 2. The only exception was the P-instance of the novice designer. On average, the expert had more linkages than the novice. It is notice worthy that 77% of the expert's depictions were function-bounded. This means his drawings were meaningful and close connected to his conceptual reasoning.

Percentage (%)	Novice (SM01)		Expert (EM01)	
	Function-bounded	Non-function-bounded	Function-bounded	Non-function-bounded
Drawing instance	63.9	36.1	77.0	23.0
Looking instance	73.7	26.3	71.8	28.2
Perceptual instance	38.5	61.5	56.1	43.9

Table 2: The percentages of function-bounded and non-function-bounded instances of the novice and the expert.

These findings describe the connections between sketches and the functional references that designers used to conceptually reason the design problem. Sketches are utilized as part of the conceptualization of some significant aspects of an experience. They are part of design knowledge of meaning-based representation. The concepts and meanings of a design are stored in its representation so that we can see it is important in design education and practice to learn knowledge through reading drawings and plans of famous architecture. Design research has speculated that sketches do not only present the perceptual features of design but also the functional aspects of design (Goldschmidt 2001). Here, we examined the detailed linkages between depictions and abstract ideas. They formed design knowledge of meaning-based representation. As for those non-function-bounded instances, they were unfruitful attempts in design. They had not been utilized by the designers to visually reason the design issues, but being pure external representations without connections to the content of design.

Nature of the main findings

This study attempts to elicit a holistic concept in studying design activities through the interactions between design knowledge and sketches. There are three main findings in response to it. First, there is a strong connection between design sketches and design knowledge. The details of this relationship were observed in the design process. The complex networks amongst physical actions, visuo-spatial perceptions, and functional attachments were revealed. Our empirical data showed statistically significant relationships between them. Second, there is perception-based and meaning-based design knowledge, which are concordant with human knowledge representation (Anderson 2000). The former is applied to understand sketches and discover interesting visuo-spatial relationships, while the latter is applied to visual reasoning and functional attachments. Third, design sketches are perception-related and function-associated. Drawing and looking sketches require both perception-based and meaning-based design knowledge to effectively and efficiently utilize, or the design sketches are just meaningless doodles and graffiti of designers.

In conclusion, the strong relationship between design sketches and design knowledge is established by the inter-linkages amongst physical actions, visuo-spatial perception, and function-associated conception. It is this network which constitutes the essence of design knowledge, and its complexity makes design activities interesting and arduous to understand. The concept of close connections between design knowledge and sketches has impact in design thinking, methodology, and

education. Design knowledge could not be learnt purely verbally, and sketches have to be part of design expertise. However, this concept should be extended to design media and design knowledge. The media are any kind of material designers apply to externalize ideas, to internalize visuo-spatial relationship, and more importantly to communicate reflectively with themselves and others. Hopefully, this paper could establish part of common ground for studying design activities holistically.

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