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The Roles of Sketches in Early Conceptual Design Processes

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Abstract

Design sketches are believed to play essential roles in early conceptual design processes. Exploration of how sketches are essential for the formation of new design ideas is expected to bring important implications for design education and design support systems. Little research has been done, however, to empirically examine the ways in which designers cognitively interact with their own sketches. Using a protocol analysis technique, we examined the design thoughts of an architect from the following point of view; how he drew depictions, inspected depicted elements, perceived visuo-spatial features, and thought of non-visual functional or conceptual information. The findings suggest that design sketches serve not only as external memory or as a provider of visual cues for association of non-visual information, but also as a physical setting in which design thoughts are constructed on the fly.

Introduction

Designers typically use less rigid forms of diagrammatic or pictorial representations, such as freehand sketches, in early conceptual design processes. It is widely believed that sketches play an essential role in the formation of creative ideas. Research on the roles of sketches in design processes is expected to lay the foundation for design education in the effective use of sketches and for the development of computer tools to support sketch-based design.

Relevant to this is a more general question. That is, why and how do diagrammatic or pictorial representations facilitate people's problem-solving or decision-making? The ubiquity of these representations in our everyday life, e.g. in public signs and icons, maps, textbooks, advertisement and brochures, intensifies the significance of the pursuit of this issue. Newell and Simon (1972) discussed how these representations serve as an *external memory*. Externalizing intermediate results of inference as visual tokens reduces memory load. When some of the results need to be available for furthering inference later in problem-solving, people have only to visually revisit the corresponding tokens.

Recent research has revealed more active roles of external representations. Inspecting representations allows visuo-spatial information to naturally emerge in perception (Koedinger & Anderson, 1990). Emergence of visuo-spatial information sometimes occurs in unexpected ways, because externalizing a set of ideas forces a specific organization of elements (Stenning & Oberlander, 1995). The visuo-spatial information extracted will, in turn, make a central

contribution to inference in two ways. First, it is used for inference as its major component. This is the case where the information extracted corresponds to a meaningful predicate in the domain, for example, "equalness" in size in geometry proof problem-solving (Gelernter, 1963), and "adjacent" arrangement of components of a device in physics problem-solving (Narayanan, Suwa & Motoda, 1994). In these cases, external representations serve as a *spatial model*, providing a concrete appearance of the problem-structure and thereby encouraging people to attend to particular predicates.

Second, the visuo-spatial information extracted becomes the *visual cues* for association or reminding of abstract concepts, functional issues, relevant past experiences, or problem-solving strategies. Larkin and Simon (1987) discussed that proximity on a diagram could be a good guide for solvers to decide what to infer next. Petre (1995) discussed that indentation, alignment, white space, and symmetry in the notation of programming language help people understand the structure of programming components and their functional relationships.

These views, especially the view *as a provider of visual cues*, apply to design sketches as well. Arnheim (1977) enumerated many examples in which forms of architecture, e.g. shapes, sizes, and spatial arrangements of elements, carry abstract meanings, functions and psychological effects on people for which the architecture is designed. Suwa and Tversky (1997) suggested that experts' tendency to maintain a successive chain of related thoughts is attributable to the ability to use visual cues for association of functions. Further, designers tend to associate a visuo-spatial feature with one concept at a time and then with another afterwards (Goel, 1995; Goldschmidt, 1991). This act, called re-interpretation, is believed to be involved in the formation of creative ideas.

Design sketches have another important characteristic. They are not something given to designers at the beginning of a task, but something which designers dynamically produce from scratch during the process. By putting ideas down on paper and inspecting them, designers see new features and relations that suggest ways to refine and revise their ideas, and thereby are driven to draw again. Schon and Wiggins (1992) discussed that this sort of interaction with sketches is the essence of early design processes.

Little research has been done, however, to empirically examine how designers cognitively interact with their own sketches. What we mean by cognitive interaction is a whole set of design actions consisting of drawing, paying attention

to previously-drawn depictions, perceiving their visuo-spatial features, thinking of non-visual information and so on. How are the occurrences of these actions related to one another? We have examined the design process of a practising architect from this point of view. We employed a protocol analysis method, because of its suitability for examination of the cognitive processes of human beings (Ericsson & Simon, 1993). After a brief review of previous protocol analysis techniques, the basic idea of our coding scheme will be described. The findings of this examination have provided important views about the roles of sketches in design processes.

Protocol Analysis Techniques

Design is a typical field where protocol analysis has been intensively used. Dorst and Dijkhuis (1995) classified protocol analysis techniques used in design research into two categories; the process-oriented approach and the content-oriented approach. The former focuses on describing the structure of design processes in terms of a general taxonomy of problem-solving, i.e. problem-states, operators, plans, goals, strategies, and so on (e.g. Eastman, 1970; Akin, 1993; Purcell, Gero, Edwards, & McNeil, 1994). By contrast, the content-oriented approach aims at revealing the contents of information, resource and knowledge that are used for making inference (e.g. Schon & Wiggins, 1992; Goldschmidt, 1991; Suwa & Tversky, 1997). From our concern with designers' cognitive interaction with sketches, we have taken the content-oriented approach.

Another dichotomy in protocol analysis methods is the one between "think-aloud" and "retrospective report" techniques. The former technique, in which subjects are asked to talk aloud about their on-going thoughts while working on a given task, is regarded as a reliable method (Ericsson & Simon, 1993), and therefore has been used widely. However, it is not without disadvantages; the requirement of talking interferes with the subject's perception (Lloyd, 1995). Since this may well be fatal for examining designers' cognitive interaction with sketches, we chose to employ the "retrospective report" technique. Subjects are asked to remember and report their past thoughts after the task. This technique, too, potentially has a disadvantage, that is selective retrieval due to decay of memory, as Ericsson and Simon pointed out. One plausible measure to alleviate this problem is to allow subjects to watch the videotape of their sketching activities while reporting (Suwa & Tversky, 1997). By doing so, subjects are provided with visual cues about the exact sequence of sketching, including the timing, hesitations, returns and redrawings. Those cues apparently help subjects remember their past thoughts.

The Coding Scheme

Design Task

We used the data of a practising architect that Suwa and Tversky collected using the retrospective report technique. He has been practising for more than 20 years, to design both office buildings and natural environment. The task given to him was to design an art museum on a given site. He worked

on the task for 45 minutes while sketching on tracing paper. His sketching activities were videotaped. After the design task, he reported what he had been thinking of while drawing each stroke of his sketches.

Analysis of Protocols

Segmentation

Following the standard protocol analysis method, we segmented the entire verbal protocols. We carried out segmentation in such a way that a change in his intention and in the contents of his thoughts or actions flags the start of a new segment (Gero & McNeil, 1998; Goldschmidt, 1991; Purcell et al., 1994; Suwa & Tversky 1997). A single segment sometimes consists of one sentence and sometimes of many. The architect's protocols contained 250 segments.

Action Categories

From our concern with designers' cognitive interactions with sketches, we needed a coding scheme to classify the contents of their thoughts or actions. Among the schemes belonging to the content-oriented approach, Suwa and Tversky's (1997) is the only one that classifies the contents of information which designers attended to or thought of. The major dichotomy in their classification was between visual information and non-visual information. The former was, in turn, divided into "depicted elements" and "spatial relations", and the latter to "functions" and "knowledge". The dichotomy of visual information into elements and relations was based on the "what" vs. "where" distinction in vision and spatial cognition. So, the category of "depicted elements" includes not only evidence that designers drew elements but also one that they perceived visuo-spatial features of elements. For the purpose of our study, however, drawing and perceiving should be distinguished. We revised Suwa and Tversky's classification in the following way, still inheriting much of its concept.

Table 1: Action categories

categories	names	description or examples
physical	D-action	depict, e.g. dots, lines, symbols, words
	L-action	look at depicted elements
	M-action	move a pencil, make gestures
perceptual	P-action	perceive shapes, sizes, spatial relations
functional	F-action	conceive of functions, non-visual concepts
conceptual	E-action	evaluate aesthetic values
	G-action	set up goals
	K-action	retrieve knowledge

The first category, **physical**, refers to actions that are directly relevant to physical depictions on paper. It consists of three actions. One is to make depictions on paper, such as diagrams, symbols, annotations, memos, and sentences. We call it 'D-action'. The second is the motion of a pencil or hands that do not end up with depictions. We call it 'M-action'. The third is to pay attention to the existence of previously-drawn depictions. We call it 'L-action'.

The second category, **perceptual**, refers to actions of perceiving visuo-spatial features of depictions, such as shapes or sizes of depicted elements and spatial relations among elements. We call it 'P-action'. For example, if a designer draws a new depiction near an existing one by attending to the spatial relation between both, the new depiction is coded as a D-action, his attention to the existing depiction as a L-action, and his attention to the spatial relation as a P-action. This P-action is viewed as having occurred dependent on the D-action and the L-action. This way, P-actions have inherent dependency on physical actions.

The third category, **functional**, refers to actions of thinking of non-visual functional issues or abstract concepts with which designers associate physical depictions or their perceptual features. We call it 'F-action'. For example, if a designer attends to a spatial relation between two regions and associates it with a view from and to both places, his thought on "view" is coded as a F-action. This way, functions or abstract concepts are not actually given in the appearance of elements and relations, but suggested by it. Therefore, F-actions have inherent dependency on physical actions and/or P-actions.

The fourth category, **conceptual**, refers to actions that deal with non-visual information which is not inherently suggested by the appearance of elements and relations. There are three types. The first is to evaluate the aesthetic value of design decisions made by P- or F-actions. We call it 'E-action'. The second is to set up goals. We call it 'G-action'. A goal is sometimes set up by being triggered by P- or F-actions, or sometimes as the subgoal of an existing goal. Once a goal is set up, it in turn gives birth to other actions, i.e. G, F, P or physical, in a top-down way. The third is to retrieve knowledge for making inference. We call it 'K-action'. All the categories of actions are shown in Table 1.

The four categories correspond to the levels at which incoming information is processed in human cognition. Information is first processed sensorily, then perceptually and semantically. The sensory level corresponds to physical actions in our category, and the perceptual level to perceptual. The semantic level is more precisely divided into functional and conceptual actions, dependent on whether or not it has inherent dependency to physical or P-actions.

The coding of design actions into these categories is done for each segment of the architect's protocols.

An Example of The Coding Scheme

Figure 1 is an excerpt of the protocols 10 minutes into the design task. The architect had calculated the necessary size of the museum building and the parking lot, 40,000 and 80,000 sq. ft. respectively, and had just depicted a rectangle for the parking lot. In this excerpt, he noticed the relationship between the sizes of both, and drew a rectangle for the building by cutting the one for the parking lot in half.

This excerpt is coded as follows. By revisiting the memo (L-action), "40,000 sq. ft.", and interpreting it again as the size of the building (F-action), he set up a goal, "draw a building of this size" (G-action). His words, "OK, building is then ..", suggest the existence of this goal. In the meantime, by revisiting another memo, "80,000 sq. ft." (L-action) and interpreting it as the size of the parking lot (F-

action), he noticed that the building should be half the size of the parking lot (F-action). Discovery to this relation allowed him to decide how to accomplish the goal; that is to cut the rectangle of the parking in half. In other words, he set up new subgoals (G-actions) under the original goal. The subgoals were to look at the rectangle for the parking and then to create a new depiction with half the size. Directed by the first subgoal, he revisited the rectangle of the parking (L-action). Directed by the second subgoal, he drew a new rectangle (D-action) with half the size (P-action). The shape happened to become thin and narrow (P-action).

And then I did the same thing [*i: drew a rectangle as a museum building*]. OK, building, then, is half of that [*i: the parking*], but I thought thin at the moment. I was thinking it might be long and narrow. So, again, I drew a long narrow one which was about 40,000 sq. ft. at that time.

[*i:*] --- interpretation of the protocol

Figure 1: An excerpt of the protocols of an architect

Analysis of Cognitive Actions

Through interaction with sketches at the physical level, designers are then able to have higher interaction at the perceptual and functional levels. This way, information "emerges" in a bottom-up way. We conjectured that this bottom-up process is a key to understanding the roles of sketches. On the other hand, processes involving conceptual actions are different in nature. They are a top-down control over subsequent actions. Although top-down processes are also worth studying, they are beyond the scope of this paper. Our examination here is limited to the lower three levels of actions.

Dominant Cognitive Actions

We examined the frequency with which functional, perceptual and physical actions occurred throughout the design process. The architect produced seven sheets of sketches. Pages 1, 3 and 5 are shown in Fig.2. The triangular closed shape and a pair of parallel lines beside it in Page 1 is the property line of the site and a public road running nearby, respectively. He was asked to arrange museum buildings and other functions on this site. He stated in the report that each page represented a distinct design phase in his process. Pages 1 and 2 involved analysing both the site and the design requirements. Page 3 was the phase to roughly arrange things on the site. This arrangement became the basis of all the subsequent pages. In Page 4, called "scheme A", he explored a detailed design based on the arrangement. In Page 5, called "scheme B", he tested another way. In Page 6, called "scheme B plan", he worked on a precise building plan based on Page 5. In Page 7, called "scheme A plan", he worked on a building plan based on Page 4.

For each page, we calculated the sum total of occurrences of physical, perceptual and functional actions. Figure 3 shows, for each page, the ratio of occurrences of each type of action to the total number of occurrences of all types.

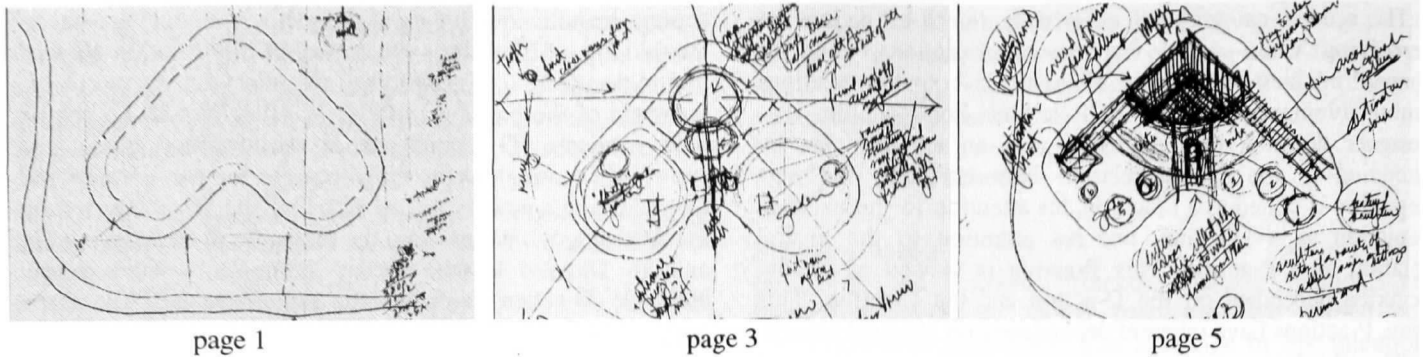


Figure 2: Sketches of a practising architect

In Pages 1 and 2, physical actions were dominant while functional actions were less frequent. In Page 3, functional actions occurred more frequently than in the first two pages, and physical actions were less dominant. In Pages 4, 5 and 6, this pattern was more salient. In Page 7, the ratios of the three actions are closer to those of Page 3. Actually, he made a new spatial arrangement, instead of the one of Page 3, in the first half of Page 7, and then explored a detailed plan on it in the latter half of the page.

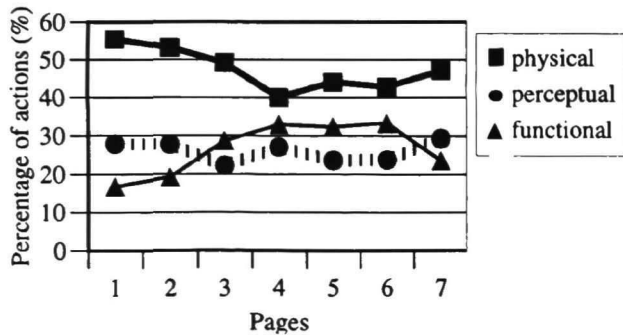


Figure 3: The occurrences of each type of action in each page

These findings brought two insights. First, his design process contained three distinct phases: problem analysis, spatial arrangement, and functional exploration. Second, in the beginning of his process, the architect made depictions and perceived their visuo-spatial features without necessarily frequent thoughts of functional issues. Rather, it took a substantial time before functional thoughts began to occur frequently.

Correlation of Different Types of Actions

We examined whether or not the frequencies of different actions changed over time in correlation with each other. This is expected to reveal how bottom-up emergence of actions happened from physical level through perceptual to functional, and thus how the architect cognitively interacted with his own sketches.

For this purpose, we needed to examine the occurrences of each type of action with a more precise granularity than just examinations of the sum total of its occurrences in each page. We chunked every five segments from the beginning of the protocols, and thereby calculated the sum total of the occurrences of each type in each 5-segment period. This way, we obtained the changes (i.e. increase or decrease) of the

frequency of each type of action with the granularity of 5-segment periods

Based on this data on the changes of each type of action, we examined whether or not there are any portions of the process in which the frequencies of two actions changed in correlation to each other. We carried out this examination for the following pairs: P- vs. L-actions, P- vs. D-actions, P- vs. M-actions, D- vs. L-actions, F- vs. P-actions, F- vs. L-actions, F- vs. D-actions, F- vs. M-actions. Statistical analyses were carried out in the following manner. First, for each 5-segment period, we calculated the difference of the frequency of each type of action from its immediately previous 5-segment period. Then, we identified the portions in which the differences for both actions correlate with each other for more than or equal to two consecutive transitions from a 5-segment period to the subsequent period. This way, the portions in which two actions happen to increase or decrease to a similar extent only for a single transition are eliminated. We did this by conducting χ -square tests on the pair of series of differences for both actions. We identified the portions in which the correlations are statistically valid with a certainty of more than 90%.

If P-actions correlated with L-actions in a period (we will call it a P-L correlation), it means two things. First, the majority of P-actions occurred during the period by being triggered by revisiting existing depictions, although P-actions could be in principle dependent on any of L-, D-, or M-actions. Second, when L-actions occurred they often induced P-actions to occur simultaneously.

The periods in which F-actions correlated with D-actions only and not with P-actions were much shorter than the periods of F-P correlation. So were the periods in which F-actions correlated with L-actions only. We found no P-M and F-M correlations. Therefore, in this paper, we will discuss only the correlations of the four pairs; P vs. L, P vs. D, D vs. L, and F vs. P.

Figure 4 shows, for each pair of actions, the periods in which there were correlations. The horizontal axis is the segment number of the architect's protocols, representing the time frame of his process. Represented along with the axis are portions corresponding to pages of his sketches. The horizontal bars represent periods of correlation. The number written near each bar is the identification number of the period, corresponding to each period number in Table 2. Table 2 shows the statistical data for each period of correlation: the duration of the correlation in terms of the

number of consecutive transitions, a χ -square value, and a certainty.

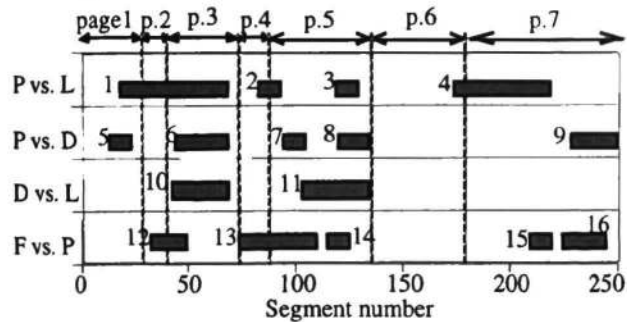


Figure 4: The periods in the design process in which there were correlations between pairs of different types of actions.

Table 2: The statistical data of periods of correlation

period number	duration of the period	χ -square value	certainty
1	10	0.699	p> 0.995
2	2	0.160	p> 0.9
3	2	0.140	p> 0.9
4	9	2.08	p> 0.99
5	2	0.039	p> 0.975
6	5	0.526	p> 0.99
7	2	0.012	p> 0.99
8	3	0.088	p> 0.99
9	4	0.880	p> 0.9
10	5	1.19	p> 0.95
11	6	1.84	p> 0.9
12	3	0.457	p> 0.9
13	7	0.972	p> 0.995
14	2	0.171	p> 0.9
15	2	0.162	p> 0.9
16	4	0.549	p> 0.95

In the entire Page 3 and the last half of Page 5, there was a co-occurrence of P-L and P-D correlations (and thus a D-L correlation at the same time). This means that perception of visuo-spatial features is induced by both drawing and revisiting existing depictions. This is characteristic of the phase of spatial arrangement, in which designers often arrange new things on a sketch by attending to the spatial relations between them and existing depictions. Actually, the architect stated that Page 3 was the phase of spatial arrangement. We recognized in his protocols that he spent the last half of Page 5 on arranging other functions on the site after having explored the detail of a building plan.

There were periods in which P-actions correlated with L-actions only and not with D-actions. This means that the majority of the architect's perceptual actions occurred in these periods when he inspected existing depictions. There were periods, too, in which P-actions correlated with D-actions only. This means that the majority of his perceptual actions occurred in these periods as soon as he made new depictions. The former periods covered 32% of the entire process, while the latter 16%. This implies that, except for the phase of

spatial arrangement, visuo-spatial features of depictions are more likely to be perceived later when the depictions are revisited rather than simultaneously when they are being drawn.

We also examined whether or not there was a negative correlation between D and L-actions. Both actions were negatively correlated in 62% of the entire process, corresponding to 76% of the periods in which there was no positive correlation. This indicates the separation of drawing actions and inspecting actions except when he worked on spatial arrangements. If drawing becomes frequent, inspecting existing depictions becomes less frequent, and vice versa.

F-actions correlated with P-actions from the latter half of Page 2 to the beginning of Page 3, for the almost entire part of Pages 4 and 5, and for the latter half of Page 7. During these periods, the major way in which F-actions occurred was to associate visuo-spatial features with functional issues, although F-actions could potentially occur by being suggested by physical actions without mediation of P-actions. Visuo-spatial information perceivable from sketches became the cues for association of functional information. Perception of visuo-spatial information itself during these periods was induced sometimes by D-actions only, L-actions only, or both.

The important characteristic true to all the three major occurrences of a F-P correlation is that it came after a P-L correlation had lasted for a while. This finding tells something about the conditions and ways in which visuo-spatial information becomes the cues for association. It will be discussed in more detail in the next section. There was a page break from Page 1 to Page 2 before the first occurrence of F-P correlation, and a break from Page 3 to Page 4 before its second occurrence. This does not, however, weaken the relationship between a F-P correlation and the preceding P-L correlation, because the architect sketched by laying a sheet of tracing paper over a previous page so that previous depictions were visible, e.g. Page 2 over Page 1, Page 4 over Page 3, and Page 5 over Page 3.

Discussion

Our analysis has provided the following insights into the roles of sketches in design processes. First, sketches serve as a representation, i.e. *external memory*, in which to leave ideas as visual tokens, so that they may be revisited later for inspection. This is supported by the negative correlation between drawing and inspection except in the phase of spatial arrangement, and by the finding that perceptual actions are more likely to occur when depictions are inspected later than while they are being made.

Second, thinking of non-visual functional issues is central to design activities. This is supported by the finding that functional actions became more and more frequent after the phase of spatial arrangement. And importantly, sketches play a role as a *provider of visuo-spatial cues* for association of functional issues. The meaningful duration of periods of F-P correlation, especially in the phase of functional exploration, supports this interpretation.

Third, the finding that a period of F-P correlation was always preceded by a period of P-L correlations provides an important insight. We interpret the period of P-L correlation

as a preparation for functional thoughts. In this period, designers create basic elements of sketches, and keep perceiving visuo-spatial information without necessarily frequent thoughts about functional issues. Only after a preparation of this sort does the entire set of visuo-spatial features become "ripe" for cueing functional issues. This interpretation is supported by the finding that there was a time delay in his design process before functional actions began to occur frequently, too. These suggest that sketches serve as something more than just a provider of visuo-spatial cues. Cognitive interaction with sketches, i.e. making depictions, inspecting and perceiving, enables designers to determine when to think of functional issues and how. Put differently, sketches serve as a physical setting in which design thoughts are constructed on the fly in a situated way. This coincides with the recently prevailing view (e.g. Agre & Chapman, 1987; Kirsh, 1995) that people act not *just* in goal-oriented or knowledge-intensive ways, but more often in response to visuo-spatial features of the physical setting they are in.

Future Work

Although our findings suggest that design thoughts occur in response to visuo-spatial features only after certain conditions are satisfied, we have not yet identified precisely what those conditions are. What sorts of visuo-spatial features do designers tend to use for cueing functional issues? Is there any patterns indicating that particular visuo-spatial cues are associated with particular functional issues?

Further, is designing in a situated way by responding to visuo-spatial features in sketches an acquired skill that only expert designers can enjoy? If so, what sorts of visuo-spatial features do experts tend to be sensitive to? What sorts of expertise are needed for using sketches in an effective way? These are the issues to be addressed in future.

Conclusion

The purpose of this study was to explore the roles of design sketches in early conceptual design processes. Conducting protocol analysis, we empirically examined the cognitive processes of a practising architect. Our examination centered around the ways in which he cognitively interacted with his own sketches. Our coding scheme, especially its classification of design actions into physical, perceptual, functional and conceptual levels, was suitable for this aim. Observing the frequencies of and the correlations between actions belonging to the lower three levels has led us to the following insights, although the generality of these insights is still an open question due to the lack of extensive number of subjects. First, sketches serve as an external memory in which to leave ideas for later inspection. Second, sketches serve as a provider of visual cues for association of functional issues. Third, most importantly, sketches serve as a physical setting in which functional thoughts are constructed on the fly in a situated way.

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