# Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions

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**Abstract** Why are freeahand sketches essential in early conceptual design processes, and how? Little research has been done, however, to empirically examine this issue. One promising approach to this is a protocol analysis to examine the cognitive processes of designers. We have devised a new scheme for coding designers' cognitive actions from video/audio design protocols. Designers' actions are coded into four cognitive levels; physical, perceptual, functional and conceptual. Relations between actions belonging to different levels, such as dependencies and triggering relations, are also coded. The present scheme has two benefits. First, we found that design actions are definable in a systematic way using the vocabulary of the scheme, and thus a designer's cognitive behaviours in each of local design stages is represented as a structure composed of defined primitive actions. This is expected to lay the foundation for microscopic analyses of how particular types of actions contribute to the formation of key design ideas. Second, this scheme is suitable for macroscopic analyses of how designers cognitively interact with their own sketches. We examined, for a practising architect, the ways in which drawing, inspection of drawings, perception, and functional thoughts correlated with one another in his design process. 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.

## 1. Introduction

Design is a kind of apprenticeship in which skills and expertise are acquired after learning basic techniques, assimilating domain-specific and general knowledge, and inspecting past good examples. The acquired expertise, however, is often tacit and implicit. Even skilled designers cannot articulate what kind of expertise they use in designing and how. This has been one of the major problems in the design community, especially in the pedagogical sense. Our long-term goal is to gain insight into design expertise, and model design processes based on it. This is expected to lead us to the establishment of design methodology for improving the quality of processes and products.

Among examples of the tacitness of design expertise is the use of freehand sketches. Skilled designers are able to capitalize on sketches especially when they are in the early conceptual design phase. Schon and Wiggins (1992) stressed the importance of freehand sketches, discussing that they are the essential medium for designers to make reflective conversation with their own ideas. Although CAD/CAM tools have had a great impact on the efficiency of design processes, it is believed that there are still aspects of designing which are uniquely associated with freehand sketches. Little research has been done, however, to empirically examine the ways in which designers use freehand sketches in design processes.

One promising approach to address this issue is to analyse the cognitive processes of designers who are working on a design task using freehand sketches. Protocol analysis has been the major technique to examine cognitive processes in design (e.g. Akin & Lin, 1995; Eastman, 1970; Eckersley, 1988; Gero & McNeill, 1998; Goldschmidt, 1991; McGinnis & Ullman, 1992; Schon & Wiggins, 1992; Suwa & Tversky, 1996, 1997b; Suwa, Gero, and Purcell, 1998). Some of these studies have found that freehand sketches play at least two important roles in design processes. One is *re-interpretation* . Drawing sketches involves associating depictions in sketches with abstract concepts, functional issues, or meanings. When designers revisit their own previous depictions, they don't necessarily interpret the depictions always with the same connotation, but sometimes tend to associate them with a new concept, functional issue or meaning. Goldschmidt (1991) observed this phenomenon, what she called "seeing-as" activity, in her study of architectural design processes, and Goel (1995) what he called "lateral transformation" in his study of graphic design processes. Another benefit of using sketches is what Schon and Wiggins (1992) called *unexpected discovery* . Externalizing a set of ideas on paper forces spatial organization and specificity in Stenning & Oberlander's sense (1995), which, in turn, by inspection afterwards, may lead to new discoveries in an unexpected way. Both re-interpretation and unexpected discoveries become the driving force for exploration of new design ideas. Put more generally, both design actions introduce discontinuity in problem-solving processes in Weisberg's sense (1993); he discussed that discontinuity in a process is a key to creative problem-solving.

The significance of these studies lies in the revelation of some of the important roles of design sketches. They have not examined, however, design processes from the following points of view. What types of design actions are possible? What structures are formed from various design actions at each of local design stages and how? How do the occurrences of different types of design actions correlate with one another? How is drawing sketches and inspecting them involved in the formation of the structure? What will the findings of these issues tell, as a whole, about the roles of freehand sketches?

In order to address these issues, we have devised a coding scheme that enables us to systematically code cognitive actions of a designer from video/audio protocols. The scheme contributes to identifying various types of design actions as well as to revealing the structure of design actions at each of local design stages. After the review of previous protocol analysis methods in the next section, the basic idea of the coding scheme will be presented. Further, using this scheme, we have analysed the cognitive process of a practising architect, in terms of the frequencies of and the correlations between different types of design actions throughout his entire design process. This examination has led us to an important view of the roles of freehand sketches in design.

## 2. Previous Protocol Analysis Methods

According to Dorst and Dijkhuis (1995), protocol analysis methods are divided into two categories; the process-oriented approach and the content-oriented approach. The former approach focuses on describing design processes in terms of a general taxonomy of problem-solving, i.e. problem-states, operators, plans, goals, strategies, and so on (e.g. Akin, 1993; Chan, 1990; Eastman, 1970; Kraus and Myer, 1970; Purcell et. al, 1994). The content-oriented approach aims at revealing the contents of what designers see, attend to, think of and retrieve from memory while designing (e.g. Goldschmidt, 1991; Schon and Wiggins, 1992). The latter approach is more suitable for examining the ways in which designers cognitively interact with their own sketches. The lack of a general taxonomy of the contents of designers' actions, however, has been the drawback of the latter approach; it has made it difficult to compare results from different designers.

One of the first attempts to devise a general taxonomy for the contents of designers' cognitive processes was Suwa and Tversky's scheme (1996). The major dichotomy in their classification of the contents was between visual information and non-visual information. The former was, in turn, divided into "depicted elements and their perceptual features" and "spatial relations". The dichotomy of visual information into elements and relations was based on the "what" vs. "where" distinction in visual and spatial cognition. Non-visual information was classified into "functional thoughts" and "knowledge". The significance of this classification is that this could become the basis for examining inherent dependencies between pieces of information belonging to different categories. For example, an architect's attention to a spatial relation between two regions in a sketch is based on the inspection of the physical depiction of each region, which belongs to "depicted elements and their perceptual features". When an architect thinks about the circulation of people from one region to another, which belongs to "functional thoughts", it occurs to his or her mind by being suggested by the appearance of a spatial relation between the two regions in the sketch. We believe that dependencies of this sort between cognitive actions belonging to different categories are the key to understanding the ways in which designers cognitively interact with their own sketches.

Suwa and Tversky's categories, however, were not necessarily developed for precisely capturing all the potential dependencies of this sort. For example, the first category "depicted elements and their perceptual features" includes not only evidence that a designer made physical depictions on paper, but also one that he or she perceived the shapes or sizes of depicted elements. From the viewpoint of the dependencies discussed, however, making depictions and perceiving their features should be distinguished from each other. We have devised a new set of categories by revising theirs.

## 3 The Coding Scheme

We have devised the current coding scheme using four sources of information. First, the concept of Suwa and Tversky's information categories is the basis for the present scheme. Second, as described later in this section, the concept on the levels of information processing in human cognition has become a reference in obtaining the major categorisation of the scheme. Third, past literature on the theories of environmental assessment (e.g. Daniel and Vining, 1983; Ulrich, 1983; Canter, 1991) was a hint for what subcategories should be provided under the major categories. We conjectured that what designers attend to or think of in designing must be close to some of the important criteria which professional assessors of designed environments employ. Fourth, intensive observation of video/audio protocols of a practising architect which Suwa & Tversky collected in their experiment (1997a) has provided an enormous amount of concrete examples from which to obtain a generalized categorisation. It was through a repeated process of setting a set of categories in a theory-oriented way and then testing it on the examples that we have finalised the coding scheme into the present form.

The task given to participants of Suwa and Tversky's experiment was to design an art museum in a given site. Participants were provided with a list of functions to be arranged in the site, the diagram of the site with its dimension and orientation specified. They worked on the task for 45 minutes while sketching on sheets of tracing paper. Their sketching activities were videotaped. After the design task, they remembered and reported what they had been thinking of or attending to in drawing each stroke of their sketches. They were asked to report while watching the videotape of their sketching activities, as the videotape was expected to serve as visual cues for remembering.

The present coding scheme has three aspects; segmentation, a set of action categories and indices of whether or not actions in a segment are new in the process. Each of them will be described in the following subsection.

### 3.1 The basic method of the scheme

#### *3.1.1 Segmentation*

As many previous protocol analysis methods have done, we divide the entire verbal protocols into small units, that is, segmentation. One way of segmentation is to divide protocols based on verbalization events such as pauses, intonations as well as syntactic markers for complete phrases and sentences (Ericsson and Simon, 1993). Pauses or syntactic markers flag the start of a new segment. Another way is to divide the protocols based on the subject's intention (e.g. Goldschmidt, 1991; Van Someren et. al, 1994; Suwa & Tversky 1997b; Gero & McNeill, 1998). For example, Goldschmidt defined a segment, what she calls a "design move", as "an act of reasoning which presents a coherent proposition pertaining to an entity that is being designed". A change in the subject's intention or the contents of their thoughts or their actions flags the start of a new segment. Consequently, a single segment sometimes consists of one sentence, and sometimes of many. We take the latter approach.

#### *3.1.2 Action Categories*

For each segment, we code cognitive actions of designers into four categories. They are physical, perceptual, functional and conceptual. This classification was obtained by revising Suwa & Tversky's information categories in such a way that the four categories correspond to the levels at which incoming information is thought to be processed in human cognition. Past literature in cognitive science supports the proposition that information coming into human cognitive processes is processed first sensorily, then perceptually and semantically. Physical actions correspond to sensory level, perceptual actions to perceptual, and both functional and conceptual to semantic.

The levels of information processing have an inherent dependency on each other; processing at an upper level is based on that at lower level(s). The action categories of our scheme inherit the same notion; a design action coded into an upper level should be inherently dependent on other actions coded into lower levels. According to this notion, when we code designers' actions into the four categories, we at the same time code the relationships among those actions, i.e. which action(s) are dependent on, suggested by, or triggered by which actions.

The first category, **physical**, refers to actions that have direct relevance to physical depictions on paper. There are three types of actions. One is to make depictions on paper, such as diagrams, figures, symbols, annotations, memos, and even sentences. We call it a D-action (see Table 1). The second is the motion of a pencil or hands that don't end up with physical depictions. We call it a M-action. The last type is to look at existing depictions. We call it a L-action. We code the first two types of actions by seeking evidence in the videotape of the designer's sketching activities. For L-actions and other actions belonging to perceptual, functional and conceptual categories, we seek evidence in the semantic contents of verbal protocols.

Table 1: Action categories

| category | names | description | examples |
|---|---|---|---|
| | D-action | make depictions | lines, circles, arrows, words |
| physical | L-action | look at previous depictions | -- |
| | M-action | other physical actions | move a pen, move elements, gesture |
| | | attend to visual features of elements | shapes, sizes, textures |
| perceptual | P-action | attend to spatial relations among elements | proximity, alignment, intersection |
| | | organise or compare elements | grouping, similarity, contrast |
| functional | F-action | explore the issues of interactions between artefacts and people/nature | functions, circulation of people, views, lighting conditions |
| | | consider psychological reactions of people | fascination, motivation, cheerfulness |
| | E-action | make preferential and aesthetic evaluations | like-dislike, good-bad, beautiful-ugly |
| conceptual | G-action | set up goals | -- |
| | K-action | retrieve knowledge | -- |

The second category, **perceptual**, refers to actions of attending to visuo-spatial features of depicted elements on sketches. We call it a P-action. This category consists of three subclasses. The first class is visual features of elements, such as their shapes, sizes, and textures. The second class is spatial relations among elements, such as proximity, remoteness, alignment, intersection, connectedness, and so on. The third class is organisations and comparisons among more than one elements, such as grouping of elements, and the similarity/uniformity and the difference/contrast of the visual features of elements. Suppose that a designer made a new depiction beside an existing depiction by attending to the proximity between both. Then, we code the following three; (1) the new depiction is coded as evidence of D-action, (2) his attention to the existing depiction is coded as evidence of L-action, and (3) his attention to the spatial relation, proximity, is coded as evidence of P-action. Further, at the same time, we code the dependency that the P-action is dependent on both D- and L-actions. This way, P-actions are inherently dependent on physical actions.

The third category, **functional**, refers to actions of conceiving of non-visual information which depicted elements and their visuo-spatial features are able to carry. This category consists of two subclasses. The first one is the issues of interactions between designed artefacts and people, or between designed artefacts and surrounding natural resources. For example, when a designer thinks of a function of an artefact in terms of how people use it, he or she is addressing the issue of interaction between people and the artefact in the practical sense. The circulation of people in a spatial configuration is the issue of interaction between people and the space in the behavioural sense. The view from one place to another in a space is the issue of interaction between people and the space in visionary sense. The mechanism of incorporating sunlight or wind in a building is the issue of interaction between designed spaces and natural resources. The first class corresponds to what we call "functions" in the narrow sense, i.e. in terms of how people use or interact with designed artefacts.

Non-visual information with which designers associate visuo-spatial features of elements, however, is not limited to this. As seen in past literature on environmental assessment and environmental cognition (e.g. Daniel and Vining, 1983; Ulrich, 1983; Canter, 1991), psychophysical or psychological responses to designed artefacts were one of the important criteria in assessing the values of designed natural environments. Therefore, it is natural to conjecture that these constitute significant parts of designers' thoughts in design processes as well. The second subclass of functional actions, therefore, is psychophysical or psychological reactions of people when they interact with designed artefacts in the various senses mentioned above. For example, when an interior designer is working on spatial arrangement in a floor plan of a shop, e.g. shelves for displaying goods and pathways among them, he or she may *not just* try to create the flow of people. The designer may also consider, for example, that a curvilinear pathway might give visitors a sense of "fascination" or "expectation" more effectively than just a straight path penetrating in the middle of the floor plan, and thus people are more easily and naturally attracted to small corners along the pathway. In this example, his or her attention to the flow of people within the shop would be coded as the first subclass of functional action, and the sense of "fascination" or "expectation" as the second class. As illustrated in this example, functional actions are not actually given in the appearance of depicted elements and/or their visuo-spatial features, but something with which designers associate visual information. We call these F-actions.

Suppose that the interior designer came to the above functional thoughts while depicting the locations of shelves so that the space for a pathway may emerge in between them. Then, we would code the following actions besides the two F-actions mentioned above;

(a) the depictions of the locations of shelves as D-actions,

(b) the meaning of those depictions, i.e. shelves, as a F-action,

(c) his or her attention to the space emerging in between as a P-action,

(d) his or her attention to the spatial relation between the emerging space and the depictions of shelves as a P-action,

(e) his or her attention to the shape of the emerging space, i.e. curvilinear, as a P-action.

At the same time, we would code the following dependencies between actions;

(f) the F-action of (b) is suggested by the D-actions of (a),

(g) the P-action of (d) is dependent on both the D-actions of (a) and the P-action of (c),

(h) the P-action of (e) is dependent on the P-action of (c),

(i) his or her thought on the flow of people (F-action) is suggested by the P-action of (c),

(j) his or her thought on the sense of "fascination" (F-action) is suggested by the P-action of (e) and by the P-action of (d).

The fourth category, **conceptual**, refer to cognitive actions that are not directly suggested by physical depictions or visuo-spatial features of elements. There are three types of actions. The first type is the designer's preferential (like-dislike) or aesthetic (beautiful-ugly, good-bad, and so on) evaluation of P-actions or F-actions. We call it an E-action. For example, if a designer evaluated a spatial pattern of the flow of people as excellent, the judgement "excellent" is coded as an E-action. Notice the difference between the second class of F-actions and E-actions. The former is an action to associate visuo-spatial features of elements with psychological reactions of people. By contrast, the latter is an action to make subjective judgement according to the designer's own standard. Considering that the design decision involved with the second class of F-actions could be a target of subjective evaluation of the designer, E-actions are higher cognitive actions to be distinguished from the second class of F-actions.

The second type of conceptual action is to set up goals. We call it a G-action. From intensive observation of the architect's protocols, we model G-actions in the following manner. A goal is sometimes born in a bottom-up way, triggered by P-actions or F-actions. Or, new subgoals are sometimes set up in a top-down way, when a designer divides the current problem into subproblems to carry out an existing goal. Once a goal is set up, it in turn gives birth to other actions in a top-down way. It may contribute to the birth of other goals, trigger retrieval of knowledge, or motivate F-, P- or physical actions.

The third type of conceptual action is retrieval of knowledge from memory. We call it a K-action. Knowledge is retrieved and then used for reasoning. We model two types of reasoning. One type is forward reasoning in which knowledge is applied to draw new information from existing information. For example, suppose that a designer drew the location of a restroom near an entrance hall, using domain knowledge that an entrance hall should have restroom(s) close to it. In this case, this piece of knowledge mediates the derivation of a new information, the 'near' relation, from both functions, 'entrance hall' and 'restroom'. The other type of reasoning is backward reasoning in which knowledge is applied to divide a problem into subproblems, thereby setting up subgoals under an existing goal. In both types of reasoning, retrieval of knowledge and its application involves producing new pieces of information or goals in a top-down way.

Table 1 presents all the action categories with their descriptions.

*3.1.3 Index of Whether or not Design Actions are New*

A design action, whether belonging to physical, perceptual, functional, or conceptual categories, may occur at a segment for the first time since the designer started working on the design task. Or, it may have occurred at a previous segment and is now being revisited. For each design action coded in a segment, we code this information, called 'index', as well. There are three indices; "new", "continual", and "revisited". If a designer makes a particular depiction, attends to a particular feature, thinks of a particular function, sets up a particular goal, or retrieves a particular piece of knowledge for the first time since he started the design session, then we code that design action as "new". If, at a segment, he continues a design action from the immediately previous segment, then we code it as "continual". If he has come back to a design action that he did at an earlier, but not contiguous, segment, then we code it as "revisited".

For example, if a designer makes a new depiction on paper, the corresponding D-action is "new". If the designer traces the lines of a previously drawn element on the same sheet of paper, the corresponding D-action is "continual" or "revisited", depending on whether the original depiction was made in the immediately previous segment or in an earlier segment. If the designer notices for the first time a spatial relation between two elements that were depicted before, his attention to the relation is "new", while the inspection of the two elements is "revisited". If the designer has worked on the shape of a pond in a given landscape several times before, and has just now depicted a certain shape for it, the depiction is a "new" D-action and his attention to the new shape is a "new" P-action, while his thought per se on the function "pond" is a "revisited" F-action.

## 3.2 Primitive Design Actions are Definable

We found that actions belonging to physical, perceptual and functional levels can be classified into a finite number of types, and that each type can be defined in a systematic way using the vocabulary of the present scheme, i.e. the index of the action itself, the categories of other actions which the target action is dependent on or suggested by, and the indices of the other actions. Tables 2, 3 and 4 show the definitions of design actions belonging to the physical, perceptual and functional level, respectively.

These definitions are derived in the following way. The index of a design action is new, continual or revisited. For each,

(1) the number of other actions which the target action is dependent on or suggested by is one or more than one,

(2) the indices of the other action(s) are new, continual or revisited,

(3) each of the other action(s) belongs to the same level as, or lower than, the target action.

The combination of these variables gives us a finite number of types of design actions. For example, if the index of a P-action is new and it is dependent on a "new" D-action, it suggests that the designer attended to a visual feature of the new depiction, such as shape, size or texture (see Pfn in Table 3). If the index of a D-action is new and it is dependent on a "revisited" L-action, it suggests that the designer made a new depiction by referring to a previous depiction. The semantics of this action is to draw in order to revise the shape, size or texture of the previous depiction (see Drf in Table 2), and therefore this action always co-occurs with Pfn. This way, we interpret the semantics of the action composed from each combination of the above variables, and if different combinations possess the same semantics, merge them into one. For example, regardless of whether a new P-action is dependent on two "revisited" L-actions, on both "revisited" and "continual" L-actions, or on both a "revisited" D-action and a "continual" L-action, all of these suggest that the designer discovered a new relation between previous depictions (Prp in Table 3). Repeating the merging process, we have come to the list of the definitions shown in Tables 2, 3 and 4.

We will explain some of the defined actions here. As we discussed earlier in this paper, unexpected discovery is believed to be one of the significant actions of which the occurrence is facilitated by the use of design sketches. We identified three types of unexpected discovery. They are discoveries of a feature of a previous depiction ("Pfp" in Table 3), of a space as ground ("Psg" in Table 3), and of a relation among previous depictions ("Prp" in Table 3), all of which pertain to the "perceptual" category. For example, suppose that a depiction intended for a pond happened to be of circular shape but the shape itself was never paid attention to by the designer when it was made. If the designer, later, revisits the depiction and talks about its circular shape, this action belongs to Pfp. The second type (Psg) is an action of discovering a space emerging in-between depictions. Put differently, it is perception of figure-ground reversal, one of the characteristics of human perception. The third type (Prp) is an action of attending to a relation, spatial or organizational, between two depictions which were made at different times in the design process and thus have never been explored together. The illustration of the coding scheme in the next subsection contains a typical example of this type.

Re-interpretation is also among important design actions, as we discussed in the Introduction. It is a new F-action that occurs by being suggested by a P-action, D-action or L-action whose index is revisited or continual ("Fre-i" in Table 4). For example, if a designer attends to a spatial relation between two depictions on the sketch that he used to associate with a view from one place to another, and at this moment associates the spatial relation with the flow of people to and from both places, this action also belongs to re-interpretation.

As far as G-actions are concerned, although we identified some distinct types and found that each of them is definable using the vocabulary of the coding scheme, we have not yet obtained a complete set of those distinct types. It is because we have not yet encountered a sufficient number of cases of the set-up of goals in the protocols, due to a problem of ambiguity in coding goals. We will mention the problem in Section 3.5. As far as E-actions and K-actions are concerned, we have not been able to systematically classify their types in our coding scheme.

Table 2: The list of the definitions of design actions which belong to "physical" level

| action ID | definition: category | definition: index | definition: dependent on | name/description |
|---|---|---|---|---|
| Drf | D-action | n. | c. or r. L-action | revise the shape, size, or texture of a depicti |
| Dc | D-action | n. | nil | create a new depiction |
| Dts | D-action | r. or c. | nil | trace over a depiction on the same sheet of p |
| Dtd | D-action | r. or c. | c. or r. L-action | trace over a depiction on a new sheet of pap |
| Dsy | D-action | n. | n., c., or r. P-action | depict a symbol that represents a relation |
| Dwo | D-action | n. | n., c., or r. (P-, or F-) actio | write sentences or words that express ideas |
| L | L-action | r. or c. | nil | look at a previous depiction |
| Mrf | M-action | n. | n., c., or r. P-action | move a pencil, attending to relations or featu |
| Mod | M-action | n. | c. or r. L-action | move a pencil over a previous depicti |
| Ma | M-action | n., c., or | c. or r. L-action | move a depiction against the sheet beneat |
| Mut | impossible to define by our coding schem | | | use tools |
| Mge | impossible to define by our coding schem | | | hand gestures |

Note: n., c., and r. denote "new", "continual" and "revisited", respectiv

Table 3: The list of the definitions of design actions which belong to "perceptual" level

| action ID | definition: category | definition: index | definition: dependent on | name/description |
|---|---|---|---|---|
| Psg | P-action | n. | nil | discover a space as ground |
| Pfn | P-action | n. | n. D-action | attend to the feature of a new depictio |
| Pfnp | P-action | n. | n. P-action | attend to the feature of a new relation or Ps |
| Pfp | P-action | n. | c. or r. (L-, D-, or P-) action | discover a new feature of an existing depictio of Psg, or of Prsg |
| Prp | P-action | n. | two c. or r. (L-, D-, or P-) actions | discover a spatial or organizational relatio |
| Prnp | P-action | n. | n. (D- or P-) action & c. or r. (L-, D-, or P-) action | create or attend to a new relation between a n depiction and an existing one |
| Prn | P-action | n. | two n. (D-, or P-) actions | create or attend to a new relation between tv new depictions or Psg |
| Pcf | P-action | c. | c. (L-, D-, or P-) action | continually attend to a feature |
| Pcr | P-action | c. | two c. (L-, D-, or P-) actions | continually attend to a relation |
| Pcsg | P-action | c. | nil | continually attend to a space as ground |
| Prf | P-action | r. | c. or r. (L-, D-, or P-)action | remember a feature of a depiction |
| Prr | P-action | r. | two c., or r. (L-, D-, or P-) acti | remember a spatial or organizational relatio |
| Prsg | P-action | r. | nil | remember a space as ground |
| Pipr | P-action | r. | n. (D- or P-) action & c. or r. (L-, D-, or P-) action | implement a previously mentioned relation b giving new depictions or features |

Note: n., c., and r. denote "new", "continual" and "revisited", respectiv

Table 4: The list of the definitions of design actions which belong to "functional" level

| action ID | definition: category | definition: index | definition: suggested by | name/description |
|---|---|---|---|---|
| Fnp | F-action | n. | nil | think of a function independently of depictions |
| Fn | F-action | n. | n. (P-, D-, or L-) actio | associate a new depiction, feature or relatio with a new function |
| Fre-i | F-action | n. | c. or r. (L-, D-, or P-) action | re-interpretation |
| Fcp | F-action | c. | nil | continually think of a function independently of depictions |
| Fc | F-action | c. | c. (L-, D-, or P-) action | continually think of a function |
| Fr | F-action | r. | c. or r. (L-, D-, or P-) action | remember a function |
| Frp | F-action | r. | nil | remember a function independently of depiction |
| Fi | F-action | c. or r. | n. (P-, D-, or L-) action | implement a previously explored function by creating a new depiction, feature or relation |

Note: n., c., and r. denote "new", "continual" and "revisited", respectiv

## 3.3 An Example of the Coding Scheme

Figure 1 is an excerpt from the protocols of a practising architect 10 minutes into the design task. We have inserted the interpretation, denoted as (i: ..), inducible from the circumstance in which this protocol occurred. We have also inserted the descriptions of his actions, denoted as [action: ...], such as drawing or gesturing in this protocol. He had spent the very beginning period of his design process on estimating the required sizes of a museum building and a parking lot as 40,000 and 80,000 sq. ft. respectively. And just before coming to this excerpt, he had depicted a rectangle for the parking lot with that size. This excerpt describes his thoughts when and just after he drew a region for the museum building. He drew it, attending to the relationship at this moment that the building should be half the size of the parking lot, and then happened to discover how big it appeared against the size of the entire site. This excerpt should be divided into two segments, because the creation of something and the discovery of its feature are clearly distinct events.

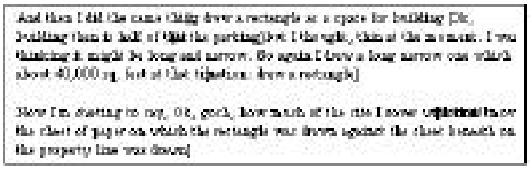

Figure 1: An excerpt of the protocols of a practising architect

Figures 2a and 2b show a structure of frames with various slots into which the contents of designer's actions in a single segment are coded. Actions for the two segments in Fig.1 were coded as such, respectively. The entire structure of one segment consists of four parts, corresponding to the four major action categories, and each is in turn divided into the subcategories that were shown in Table 1. Each row under each of the major or sub-categories is a frame corresponding to a single action. A single frame contains some of the following slots. The **ID** slot denotes the type of action whose definition was presented in Section 3.2. If there is more than one action of the same type in a single segment, number subscripts are attached for differentiation. The **index** slot denotes whether the action is new, continual or revisited. The **content** slot denotes the content of the action. Both **dependent-on** and **suggested-by** slots denote a pointer to other action(s) of the same or lower levels which the action is inherently dependent on and suggested by, respectively. The **triggered-by** slot denotes a pointer to other action(s) which triggered the occurrence of the goal or the retrieval of knowledge. The **trigger** slot denotes a pointer to other actions which the corresponding goal triggered. The **applied-to** and **produced** slots denote the following; the new piece(s) of information filled in the produced slot were derived as a result of reasoning, whether forward or backward, using the piece(s) of information filled in the applied-to slot and the corresponding knowledge.

We interpreted the first segment and coded his thoughts then in the following way. While revisiting the memo "40,000 sq. ft." (L2 in Fig. 2a) that he had left on a sketch, and interpreting it again as the size of the building (Fr), he set up a goal, "draw a building of this size on paper" (G1). His words, "OK, building is then ..", suggest the existence of this goal. Because he noticed that the building should be half (Fnp) the size of the parking lot, he decided to cut the rectangle for the parking lot in half. We interpret that he at this moment divided the problem into two subproblems; looking at the rectangle and creating a new depiction with half the size. He set up the corresponding subgoals (G2 and G3) under the original goal G1 Attention to the relation (Fnp) triggered a piece of domain-independent strategy (K2) for setting up those subgoals. G2 triggered the action to look at the rectangle for the parking lot (L1). G3 triggered the action to draw the rectangle (Dc) so that its size (Pfn2) appears to be half the size (Prnp) of the rectangle for the parking. The shape of the new rectangle happened to be thin and narrow (Pfn1). He gave the new rectangle a meaning, "building" (Fi), that he had already talked about before. Figure 3a shows how the design actions in this segment relate to each other. There are two kinds of relations. One is a dependency such as 'dependent-on' or 'suggested-by'. It is denoted as a line. The other is a relation that represents the order in which actions occur, such as triggered-by, trigger, or produce. It is denoted as an arrow.

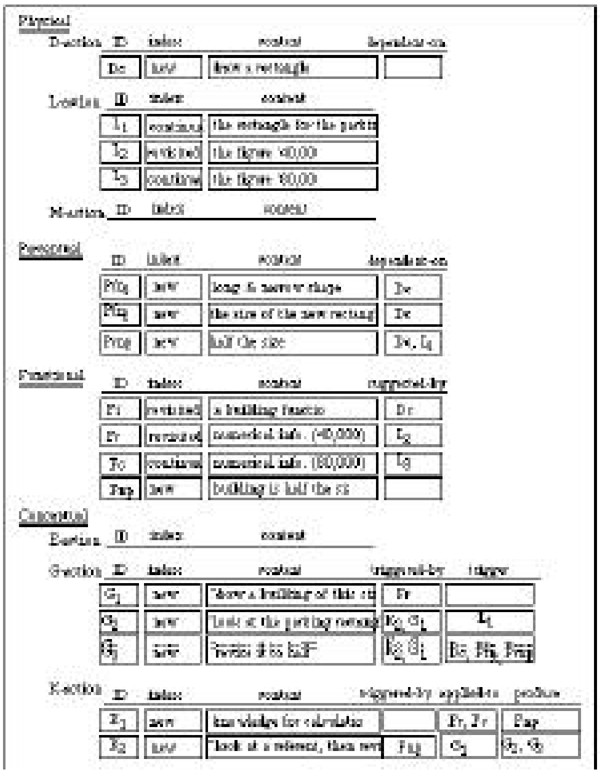

Figure 2a: The coding of the first segment shown in Figure 1.

We code the second segment as follows. The architect for the first time noticed the necessity to compare the rectangle for the building with the entire site (Prp in Fig.2b). This P-action per se is "new" and is dependent on the "continual" attention to the rectangle (L2) and on a "revisited" attention to the entire site (L1). This is a typical example of the third type of unexpected discovery that we discussed in Section 3.2. The comparison, then, triggered the set-up of a goal, "try different ways of comparison between both" (G1), which in turn motivated the action to move around the rectangle against the entire site (Ma). Wherever he moved the rectangle within the site, he figured out (E1) that the size of the building (Pc) is too large within the site. This evaluation was mediated by a piece of knowledge (K1) although this excerpt does not present information about what kind of knowledge it was. Figure 3b shows the relations among the design actions in this segment.

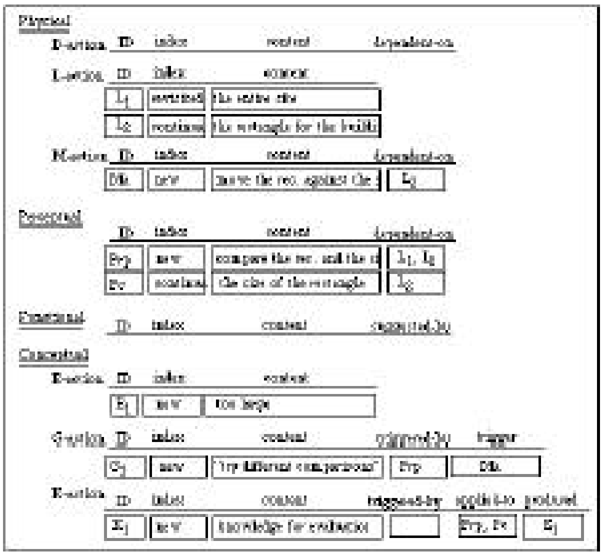

Figure 2b: The coding of the second segment shown in Figure 1.

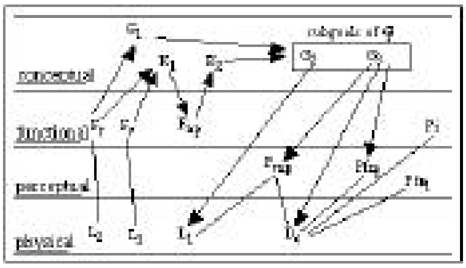


Figure 3a: The relations among the design actions that constitute the first segment in Figure 1.

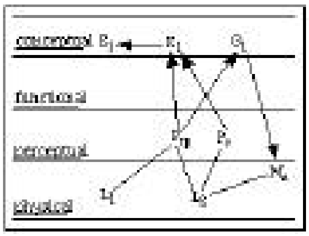


Figure 3b: The relations among the design actions that constitute the second segment in Figure 1.

## 3.4 The Benefits of the Scheme

The present coding scheme has two benefits. First, as discussed in Section 3.2, we are able to derive the definitions of primitive design actions in a systematic way, using the vocabulary of the scheme. As a consequence, design behaviours of a designer in each segment can be represented as a structure consisting of those defined actions, as illustrated in Figures 3a and 3b. This will provide the basis for dissecting the structures of a designer's cognitive processes at the segment level. For example, which primitive actions play essential roles in a designer's process and how? What is the origin of the birth of creative ideas? Do they happen to emerge in a bottom-up way, or occur in a top-down way by being controlled by conceptual actions?

For full-fledged analysis from this point of view, however, there remains items to be resolved. For some, if not all, segments in the protocols, we have been faced with an ambiguity in coding the set-up of goals that are one of the important determinants for the structure of design actions. Although we could make microscopic analyses only from the segments free from ambiguity, it may weaken the feasibility of the results of the analyses. The cause of this ambiguity problem and the measures that we will have to take against it will be discussed in Section 3.5.

Second, since the four action categories correspond to the cognitive levels of information processing, the present scheme enables macroscopic analyses of design processes from the following points of view.

(i) Do actions belonging to particular cognitive levels dominate in particular design phases in the process? If so, what levels of actions are dominant in what phases?

(ii) Do actions belonging to a particular level tend to occur in correlation with those belonging to another level?

Examination of the ways in which actions of a designer belonging to different cognitive levels interact with one another is expected to reveal important insights into the roles of sketches in design processes. The present scheme is suitable for this analysis. The results of this analysis will be described in Section 4.

## 3.5 Current Limitation

We have encountered a problem that the contents of designers' protocols in some segments are too ambiguous to code the set-up of goals with a unique interpretation. For example, let's think of coding the excerpt of protocols shown in Figure 4. Here, the architect gave an arc shape to the museum building. The verbal protocols, however, do not present enough evidence to determine which of the following interpretations is more plausible. One interpretation is that the arc shape was born first without explicit reasons or considerations, and then he found that the shape is beneficial because it affords a 'fanned' view from the building to many directions. Another interpretation is that a goal "to create a nice view from the building" was born first somehow, and then the arc shape was selected because he possessed a piece of knowledge that the shape would create a nice view. The first is to interpret that the architect's thoughts occurred purely in a bottom-up way from the spontaneous birth of the shape, while the second is to interpret that the shape was intentionally created through mediation of a goal and a piece of domain knowledge. The highly ambiguous word, "response", is problematic in this example.

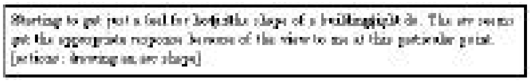

Figure 4: An excerpt of the protocol of a practising architect that allows for multiple interpretations

We suspect that the source of this problem may lie in a disadvantage of the retrospective report method. In reporting their past thoughts, designers may frequently have difficulty in remembering the subtle order in which they set up goals, and did other types of actions. Because of this, designers sometimes report in too much a compact and ambiguous way, as illustrated by this architect's word "response". Ericcson and Simon (1993) discussed that the reports of past thoughts tend to be easily biased by specific cues implicitly included in the instructions about reporting. In order to alleviate this problem, Suwa and Tversky chose to show subjects the videotape of their own sketching activities in reporting. Subjects were provided with visuo-spatial cues about the exact sequence of sketching, including the timing, hesitations, returns and redrawings. Those cues apparently worked well to enable designers to remember their functional actions, because functional information is something which they have associated those visual cues with in designing. Unlike functional actions, however, conceptual actions are not inherently suggested by visuo-spatial cues. Visual information in the videotape of their own sketching activities, therefore, does not serve as cues for remembering conceptual actions.

We suspect that the use of the "think-aloud" technique might be able to alleviate this problem, because people are presumed to verbalize their thoughts in the exact order in which they happen. Employing the present coding scheme for analyses of protocols collected by the think-aloud method is one of the next steps. Further, accumulating the experience of coding conceptual actions from protocols of retrospective reports for more number of designers is also required. These are expected to bring insights into the conditions in which, and the reasons why, reports about the set-up of goals tend to be ambiguous.

# 4 Macroscopic Analyses of Design Processes

Through interaction with sketches at the physical level, designers are then able to have higher interaction at the perceptual and functional levels. This is a process in which design actions emerge in a bottom-up fashion. By contrast, processes involving conceptual actions are a top-down control over subsequent actions. In this paper, our examination based on the present coding scheme is focused on processes of the former type.

## 4.1 Dominant Cognitive Actions

We examined the frequency with which functional, perceptual and physical actions occurred throughout the design process of the architect. He produced seven pages of sketches. They are shown in Figure 5. The triangular closed shape in Page 1 is the property line of the site given to him. He was asked to arrange museum buildings and other functions on this site. Also given were a pair of parallel lines representing a public road that runs from the west of the site to the south. He stated in the report that each page represented a distinct design phase in the 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 one possible 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.

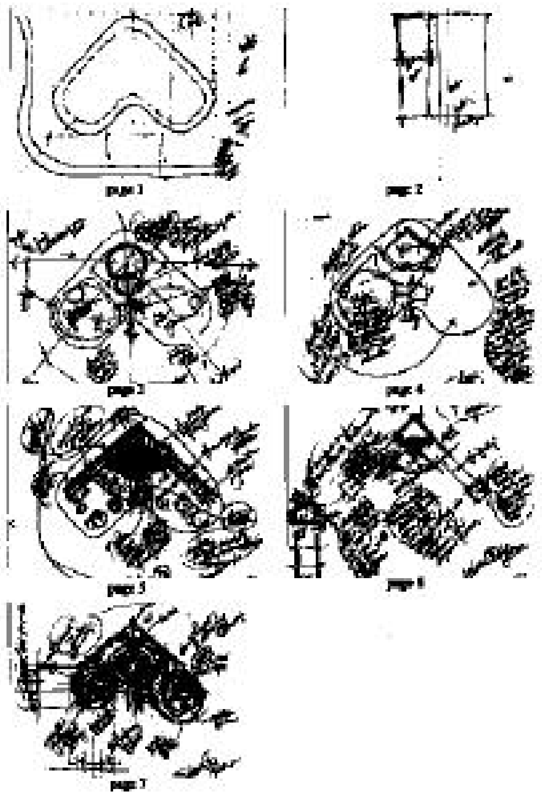

Figure 5

For each page, we calculated the sum total of occurrences of physical, perceptual and functional actions. Figure 6 shows, for each page, the ratio of occurrences of each type of action to the total number of occurrences of all types. 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, functional actions became less frequent again, while physical actions increased a little. This tendency is closer to that of Page 3. Actually, in the first half of Page 7, he discarded some of the basic arrangement he had made in Page 3 and tried a new arrangement with which to explore a detailed building plan in the latter half of the page.

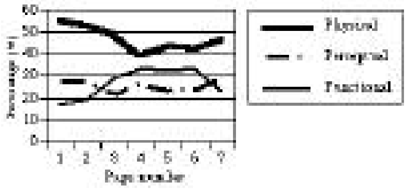


Figure 6: The occurrences of each type of action in each page

These findings have two implications. First, his design process contained three distinct phases: problem analysis, spatial arrangement, and functional exploration. Second, the occurrences of functional and physical actions capture the characteristic of each design phase. Functional actions occur more frequently in the phase of functional exploration than in other phases. Physical actions dominate in the phase of problem analysis. The phase of spatial arrangement is intermediate between the two.

## 4.2 Correlation of Different Types of Actions

*4.2.1 Correlation between P-actions and others*

We examined whether or not there were any periods in which the frequencies of the occurrences of different actions changed over time in correlation with each other. This was 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 frequency of the occurrences of each type of action with a more precise granularity than just an examination of the sum total of its occurrences in each page and comparisons between pages. 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. We did this because segment-by-segment changes of the frequency of actions may be too sharp to extract any general tendencies from them. Then, we normalized the actual frequency of each type of action in each 5-segment period, by dividing it by its average frequency over the entire process. We did this because it might be better to compare different types of actions by removing the magnitude of frequency specific to each type.

Figure 7 shows how the frequencies of occurrences of P-actions and L-actions changed over time throughout the entire process. The horizontal axis is the segment number, representing the time frame in which the design proceeded. Shown on the bottom are the periods of time corresponding to the pages of the designer's sketches. The vertical axis represents the frequency of the occurrences of each type of action, normalized in the way mentioned earlier. As the vertical value we use *(Fx-Fxavg)/Fxavg*, where *Fx* is the actual frequency of *X* -actions and *Fxavg* is the average frequency throughout the process. 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 looking at 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. It can be observed that both actions vary in correlation with each other in Pages 2 and 3, and in the beginning to Page 7.

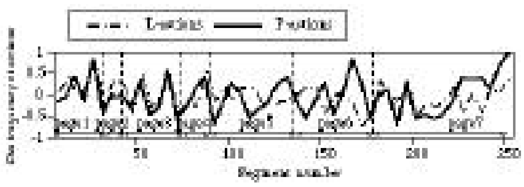


Figure 7. The correlation between P-actions and L-actions.

We examined the correlation of different types of actions 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. Rather than visual analyses of the graphs of correlations such as Figure 7 for each pair, we carried out statistical analyses to identify the portions of the process in which there was a correlation between both in each pair. 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 of the process 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 in the same direction only for a single transition are eliminated. We did this by conducting $\chi$-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%.

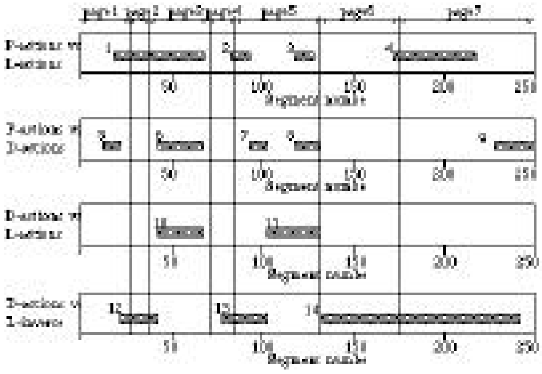

Figure 8. The portions of design process in which there are correlations between two actions for the pairs that are concerned with P-actions.

Figure 8 shows, for each pair of actions that are concerned with P-actions, the periods in which there was a correlation. The horizontal axis is the segment number, thus representing the time frame. The horizontal bars show the periods of correlation. The number written beside each bar is the identification number of the period, corresponding to each ID number in Table 5. Table 5 shows, for each period of correlation, the corresponding statistical data, i.e. the duration of the period in terms of the number of consecutive transitions, a $\chi$-square value, and a certainty. The pairs of actions for which there was no correlation throughout the process are not shown here. For D- and L-actions, we examined whether or not both actions have a negative effect on each other, by performing the same statistical analysis on the pairs of the period-to-period differences of D-actions and the inverse period-to-period differences of L-actions.

Table 5. The statistical data of the portions of correlation

| ID. of portion | consecutive transitions | $\chi$-square value | certainty (p>) | ID. of portion | consecutive transitions | $\chi$-square value | certainty (p>) |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 0.699 | 0.995 | 15 | 3 | 0.457 | 0.9 |
| 2 | 2 | 0.160 | 0.9 | 16 | 7 | 0.972 | 0.995 |
| 3 | 2 | 0.140 | 0.9 | 17 | 2 | 0.171 | 0.9 |
| 4 | 9 | 2.08 | 0.99 | 18 | 2 | 0.162 | 0.9 |
| 5 | 2 | 0.039 | 0.975 | 19 | 4 | 0.549 | 0.95 |
| 6 | 5 | 0.526 | 0.99 | 20 | 5 | 0.704 | 0.975 |
| 7 | 2 | 0.012 | 0.99 | 21 | 3 | 0.456 | 0.9 |
| 8 | 3 | 0.088 | 0.99 | 22 | 3 | 0.310 | 0.95 |
| 9 | 4 | 0.880 | 0.9 | 23 | 4 | 0.291 | 0.99 |
| 10 | 5 | 1.19 | 0.95 | 24 | 2 | 0.136 | 0.9 |
| 11 | 6 | 1.84 | 0.9 | 25 | 2 | 0.062 | 0.95 |
| 12 | 4 | 0.680 | 0.95 | 26 | 5 | 0.900 | 0.95 |
| 13 | 5 | 0.950 | 0.95 | 27 | 3 | 0.404 | 0.9 |
| 14 | 22 | 8.80 | 0.99 | 28 | 2 | 0.198 | 0.9 |
| | | | | 29 | 5 | 0.631 | 0.975 |

There are two periods in which P-actions correlated with both L- and D-actions; almost the entire part of Page 3 and the end of Page 5. In these periods, the designer drew and looked at existing depictions simultaneously, and both induced his perceptual actions. The majority of perceptual actions which occurred were dependent on both actions. This may be characteristic of the phase of spatial arrangement in which things are arranged on a sketch by attending to the spatial relations between themselves and existing depictions. We recognized in his protocols that he spent the ending portion of Page 5 on arranging sculptures and ponds in the remaining area of his sketch, after he had explored the details of the building plan.

The periods in which P-actions correlated with L-actions only and not with D-actions were longer that those in which P-actions correlated with D-actions only. The former periods cover 32% of the entire process, while the latter 16%. This suggests that perceptual actions were more likely to occur later when he inspected existing depictions in a "revisited" way than simultaneously when he was making depictions, except for the phase of spatial arrangement.

For almost all the parts of the process except for the phase of spatial arrangement, drawing and looking at existing depictions have a negative effect on each other. 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 clearly indicates a separation between drawing and inspecting. If drawing becomes frequent, looking at existing depictions becomes less frequent, and vice versa.

These findings about P-actions have led to the following insight. Except for the phase of spatial arrangement, the role of drawing is to leave ideas down on a sketch as visual tokens, so that they can be revisited later for inspection. This inspection will then stimulate perception.

*4.2.2 Correlation between F-actions and others*

Figure 9 shows that F-actions correlated with P-actions from the last half of Page 2 through the beginning of Page 3, for almost the entire part of Pages 4 and 5, and for the latter half of Page 7. This means that 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. This means that visuo-spatial information perceivable from sketches became the cues for association of functional information during these periods.

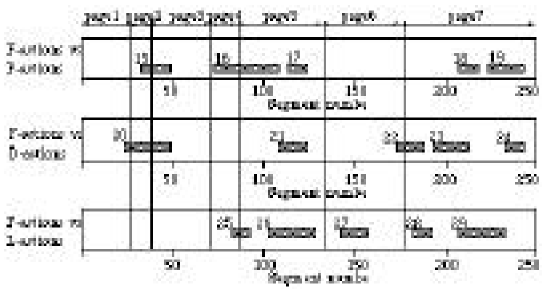

Figure 9. The portions of design process in which there are correlations between two actions for the pairs that are concerned with F-actions.

The important characteristic true to all the three major occurrences of F-P correlations is that it came after a P-L correlation had lasted for a while (compare Figure 4 and 5). This finding has an implication for the conditions and ways in which visuo-spatial information becomes the cues for association. This will be discussed in more detail in Section 5.

Since we have defined the action of unexpected discoveries as a particular type of P-actions, we examined how F-actions correlated with this particular type of P-actions. We did not conduct statistical analysis for this, because the frequency of the occurrence of unexpected discoveries was relatively fewer than F-actions, and the normalization mentioned earlier tends to exaggerate the fluctuation of unexpected discoveries more than F-actions. Instead, we visually analysed the correlation between both. Figure 10 shows, for Pages 4 and 5, the frequency of F-actions, unexpected discoveries, and the remaining P-actions. The vertical axis is the actual frequency. The peaks of F-actions correlated more with the increase of unexpected discoveries than with that of the remaining types of P-actions. In the latter half of Page 7, where F-actions correlate with P-actions, there was no such tendency.

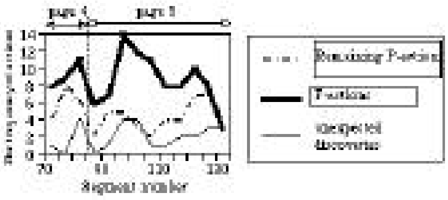

Figure 10. The correlation between F-actions, unexpected discoveries and the remaining P-actions.

F-actions correlated with D-actions only without the mediation of P-actions, in the beginning of Page 2 and in the first half of Page 7. During these periods, the majority of F-actions occurred in such a way that the designer named what he was drawing. F-actions correlated with L-actions only, for some portions of Page 6. The majority of F-actions occurred in such a way that he remembered the meanings of depictions when he re-inspected them. The duration of these correlations, however, were much shorter than the periods of F-P correlation.

These findings about F-actions have led to the following insights. First, the phase of functional exploration can be characterized by the phenomenon that the majority of F-actions occur by being suggested by P-actions, not just by physical actions. Designers perceive visuo-spatial features from sketches and use them as cues for thinking about non-visual information, such as functional issues or psychological effects. Second, visuo-spatial features discovered in an unexpected way may sometimes, though not always, become the cues for F-actions. This is a hypothesis to be examined by seeking data on more designers.

## 5 Discussion: The Roles of Design Sketches

The professionalism of expert designers has been attributed to their possession of domain knowledge and problem-solving strategies and to their ability to develop appropriate plans and goals. Thus, much emphasis has been put on the examination of how they use problem-solving strategies, plans, goals and knowledge. Most process-oriented protocol analysis addressed this issue. This tendency has been prevalent in the artificial intelligence community as well. Experts' intelligent behaviors have been attributed to domain knowledge. The present study, however, has shed light on another important factor in design. Knowledge, strategies, goals and plans do not always initiate or control design actions. Rather, perceptual and physical actions play central roles in many ways.

Actually, we have obtained the following insights into the roles of sketches in design processes.

(1) 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.

(2) 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.

(3) 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 suggests 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.

## 6 Conclusion

We devised a new scheme to code cognitive actions of designers from their video/audio protocols. Their actions were coded into four major categories that correspond to the cognitive levels of information processing, i.e. physical, perceptual, functional and conceptual. Each major category, in turn, was classified into subcategories. Relations between actions belonging to different actions, such as dependencies and triggering relations, are also coded.

We found that designers' cognitive actions are definable in a systematic way using the vocabulary of the present coding scheme. As a consequence, a designer's cognitive behaviours in each of local design stages is represented as a structure composed of defined primitive actions. Although the problem of ambiguity in coding the set-up of goals for some segments of design processes is yet to be resolved, this has the potential to provide the basis for microscopic analyses of how particular types of actions contribute to the formation of key design ideas.

We made macroscopic analyses, for a practising architect, of how he cognitively interacted with his own sketches. Observing the frequencies of and the correlations between actions belonging to physical, perceptual and functional levels has led us to the following insights. 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.

## Acknowledgment

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