The Anatomy of the Design Process Revealed by DCOCS

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Abstract: There have been many design protocol studies exploring different aspects of the design process, but few of these researches have been methodologically repeated. The purpose of this paper is to propose a systematic framework by which systematical exploration of the complex structure of the design process is possible. It is named DCOCS that has been applied in various papers. This study presented the refined procedure and details in the hope that DCOCS could be applied by more design researchers. The anatomy of the design process is revealed by segments, levels, instances, and types of DCOCS. The dependencies among physical, perceptual, and functional levels are also examined. Based on these encoded results, some possible directions of applying DCOCS have been proposed. The detailed structure of the design process could be examined from four different perspectives: transcripts-oriented, frequency-oriented, segment-oriented, and instance-oriented. The importance of this paper lies on the methodological discussions that results from our previous studies.

Key words: Protocol Studies, the Design Process, Design Cognition

1. Introduction

After the first design protocol study, protocol analysis has been widely applied in design community (Cross, 2001), and the delft design conference further established its methodological position (Cross, Christiaans, & Dorst, 1996). Currently, protocol analysis has become the standard experimental technique for exploring the cognitive activities of designing (Ericsson & Simon, 1993; van Someren, Barnard, & Sandberg, 1994; Cross et al., 1996). Two types of protocol approaches have been developed: concurrent and retrospective (Dorst & Dijkhuis, 1995). In concurrent protocols, the subjects are required to design and verbalize thoughts simultaneously. In contrast, in retrospective protocols, subjects are asked to design first and then retrospectively report the design processes with or without the visual aids. This is provided by videotapes documenting their own design processes. In general, concurrent protocols have been utilized in the process-oriented aspect of designing, which is largely based on the information processing view proposed by Simon (1992). Comparatively, retrospective protocols have been utilized in the cognitive content aspect, which is largely based on the notion of reflection-in-action proposed by Schön (1995). Normally, design researchers choose one or the other methodology to achieve their research purposes.

1.1 Concurrent and retrospective protocols

In design studies, there has been little methodological examination on the differences between the two different types of protocols, to indicate the advantages and disadvantages of them in revealing the design process. Therefore, design cognition researchers tend to apply the concurrent protocol because some researchers still have doubts about the validity of retrospective protocol. Gero & Tang (2001) have examined the differences between concurrent and retrospective protocols in terms of process-oriented aspects of designing using the coding scheme devised by Gero & McNeill (1998). The results showed that both protocols had similar characteristics, but the number of segments in the retrospective protocol was greater than that in the concurrent. Berry & Broadbent (1984) proposed similarly that the combination of the instruction and concurrent verbalization improves the performance when giving reported knowledge of the task. Being in concordance with Ericsson and Simon (1993), they proposed that concurrent and retrospective protocols are similar to each other, but that retrospective protocols may have details omitted due to the decay of long-term memory.

In terms of the contents revealed by concurrent and retrospective protocols, they were similar to certain extent as well. We could argue that concurrent verbalization can reveal the process-oriented aspects of the design process to echo the question proposed by Lloyd, Lawson & Scott (1995). It is still unclear the differences between concurrent and retrospective protocols in the content-oriented aspects of the design process. Our continuous studies of protocol analyses, however, showed that retrospective protocol revealed more information in the period when intensive sketching occurred and had the abilities to reveal the process-oriented aspects as well (Maher & Tang, 2003; Tang, 1997, 2001, 2002, 2003; Tang & Gero, 2001, 2002).

Based on these researches, this paper tried to establish the framework to explore the anatomy of the design process with retrospective protocol and one content-oriented coding scheme that is named DCOCS. Because of its complexity, the detailed structures of DCOCS were introduced in analytical process section. Potential applications were demonstrated. Finally, our previous studies resulted in the methodological discussions in this paper. Our previous studies with Gero and Maher focused on the results obtained from this method, instead of the method itself. The results in this paper however served as a role to exemplify the applicability of DCOCS.

2. Methods for Design Cognition Research

The methodology we proposed utilized an integrated process of retrospective protocol analysis and content-oriented coding scheme. The main thread follows the series of retrospective protocol studies produced by Suwa and his colleagues (Suwa, Gero, & Purcell, 2000; Suwa & Tversky, 1997; Suwa, Purcell, & Gero, 1998). Details of experimental procedures, segmentation, and the coding scheme in this research are inherited from the original setting. The definitions and refined procedures resulted from the collaboration with Professor Gero in the Key Centre of Design Computing and Cognition, the University of Sydney. They also resulted from our experience in the experiments and analyses and discussions with other design researchers. The terminologies, definitions, and processes have been modified to reflect our findings, criticism, and comments from research colleagues.

2.1 The process of experiment in this research

The experiment consisted of two parts; First, a design task in which participating designers design according to the design brief that has detailed requirements. Two cameras were utilized to record the actions and movements of designers. Using the videotape as visual cues, details of each step of sketches were reported. Second, participating designers retrospectively report the design process with the aid of the videotape. They were requested to report every thought relating to each stroke in the sketches, and steps were

1. Designing without utterance
2. Giving retrospective protocol with the aid of the mute video images of the previous section
3. A brief interview about the subjects' background and comments about the experiments.

Each experimental process produced one set of raw protocol, two videotapes, sketches, and an interview. The experimental instructions served as an adequate guide for designers in providing protocols. Since the instructions affect the outcome of designers' approach to the proposed problem, it is important to have peer-review and pilot studies.

3. Analytical Process

The analytical process consists of three primary stages: transcription, segmentation, and encoding. Transcription records the detailed visual depictions and transcribes the verbal utterances of subjects. Segmentation parses the raw protocol and depictions into small units using designers' intentions. The parsed protocol is encoded using the coding scheme to reveal the content of the design process. The encoded presents the characteristics and complex connections of the design process in terms of individual research goals.

3.1 Verbal and visual Transcripts

After experiences, the utterances of the subjects were transcribed into raw protocols that contain the time stamps and exact descriptions of voice and sound in the experiment. The following is an example extract of the verbal transcripts.

> 00:02:19 well the first thing I was trying to do is to just really understand the site. Looked at the surroundings, the features of the site where the views might be, where the sun orientation is. And to get the feel of the actual area of the site. The next thing was to…
>
> 00:02:51 to actually understand the sizes of the areas that were going to have to be put into the house. I've started off with the simplest thing, the garage. um clearly recognizing it was a double garage or carport, car accommodation. and then i went through a little exercise. Well here I am still looking at the orientation. and really understanding the site. The next thing was to understand the actual areas that have to be accommodated, so I was looking at the schedule of spaces that would have to be provided. Starting to think about the relationships between those. Unlike most houses that had a three spaces that i didn't really understand.

The sketches produced in the design process were also numbered by different categories, for instances, lines, circles, squares, annotations, and hatches, *Figure 1*. Both verbal and visual transcripts are the material used in the following encoding process

3.2 Segmentation

The raw protocol and corresponding numbered depictions were divided into small units, segments, in terms of the intentions of the subjects. Gero, McNeill, and Suwa first parsed protocols along the lines of the designer's intentions and actions (Gero & McNeill, 1998; Suwa et al., 1998), instead of verbalization events or syntactic markers (Ericsson & Simon, 1993). In the same vain, the definition of segments in this study follows as pieces of coherent information that appear to have occurred simultaneously in the designer's mind. A new segment is flagged by the shift of thought and by the change of physical instances. The length of a segment varies. Similar to the definition of "move" (Goldschmidt, 1991), a segment is the smallest units of design reasoning present, a coherent proposition pertaining to an entity that is being designed.

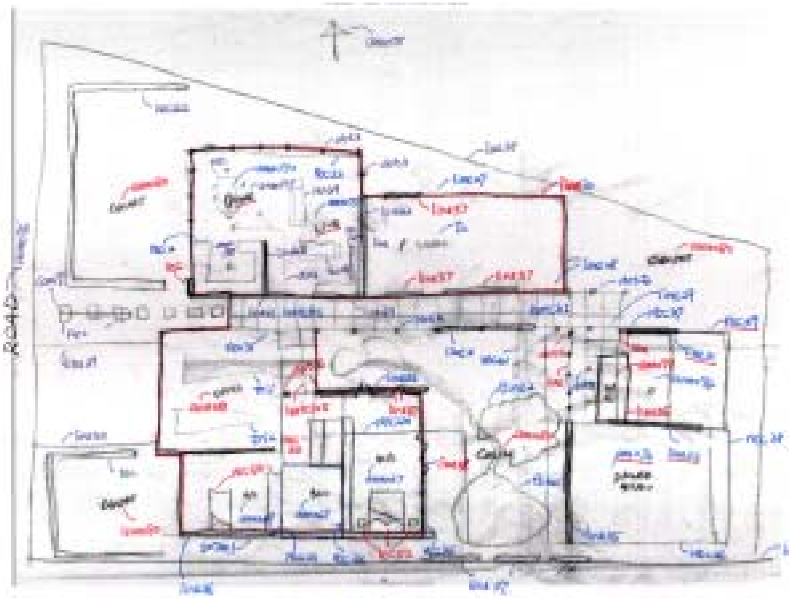


Fig.1 The numbered depictions of visual transcripts

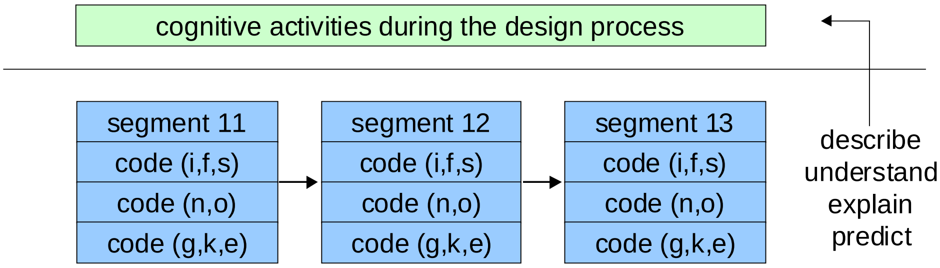


Fig.2 Functions of a content-oriented coding scheme

The coders, consequently, determine the relationship between a segment and its corresponding drawings and looking instances. During the segmentation process, revisiting the video by different coders could resolve the ambiguity in determining the relationship between a segment and its corresponding physical instances. It often occurred with rapid and continuous drawing actions.

3.3 Content-oriented coding scheme

A coding scheme is the collection of the codes used to represent the design process. It is postulated as a representational system to describe, understand, explain, and even predict the cognitive activities during the design process, *Figure 2*. It plays an important in design protocol studies.

The coding scheme we utilized was established by Suwa, Purcell, and Gero in 1998 and further modified in 2000 (Suwa et al., 2000). It has been applied in this research through a series of studies. This scheme is an attempt to understand the cognitive aspects of the design process. It consists of four cognitive levels that imply a sequential process in which a stimulus goes from the external world to the internal world and vise versa. We named it the design content-oriented coding scheme, in short DCOCS (pronounce as dee-cokes). Its details are refined in this research in terms of levels, instances, index, class, content, and type, and dependency. The definitions listed here are an refined version of the original definitions, based on the evolution and experience of our continuous research (Maher & Tang, 2003; Tang, 1997, 2001, 2002, 2003; Tang & Gero, 2001, 2002;).

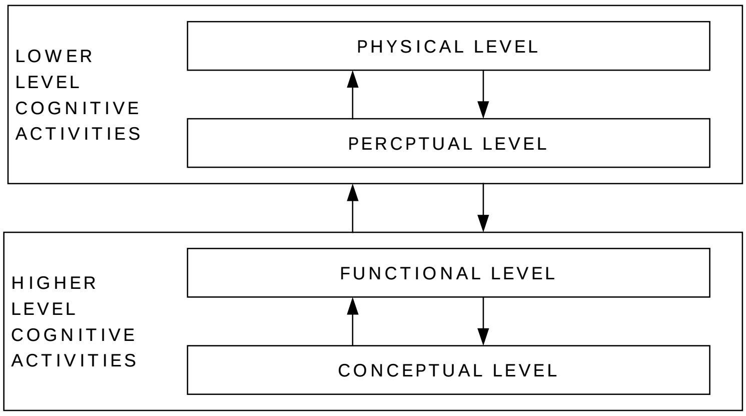


Fig.3 The four cognitive levels of DCOCS

3.4 Levels

The four cognitive levels in DCOCS are physical, perceptual, functional, and conceptual, *Figure 3*. The first level, physical, refers to the process having direct relevance to the external world, comprising drawing, looking, and other physical actions.

The second level, perceptual, concerns the process attending to visuo-spatial features and relationships. The third level, functional, relates to the process consisting of functional references mapped between visuo-spatial features/relationship and abstract concepts including meanings and functions. The fourth level, conceptual, represents the internal abstract conceptual thinking process. An episode of the design process, consequently, is represented by a series of consecutive segments that is analyzed by these four levels and their inter-linked relationships. The physical and perceptual levels analyze the lower level cognitive activities that interact with the external world of designers, *Figure 3*. In practice, the sketches and videotapes are the main resources for determining lower level activities. Functional and conceptual levels analyze the higher level cognitive activities that relate to the internal world of designers, *Figure.3*. The protocol is the main resource for them. The four cognitive levels in a segment have trends of occurrence but the exact chronological order is hard to determine.

3.5 Instances

The instance in DCOCS refers to an observed occurrence of a specific cognitive action in a level; for example, depicting a line is a drawing instance in the physical level. What “instance” describes is an occurrence of an event; therefore, it could be physical, perceptual, functional, and conceptual. There are three kinds of instances in the physical level: drawing instance (D-instance), looking instance (L-instance), and other physical instances (O-instance). No further categorizing was undertaken for the other levels. Each level may have more than one instance or have no instance at all. The number of instances in different cognitive levels depends on the corresponding behaviors of the participating designers revealed by videos, sketches, and protocols. There might be, however, no instance on a level, and this level is missing in a segment.

3.6 Index, Class, and Content

The index in DCOCS is given to show the occurrence of the instances in the physical, perceptual, and functional levels. An index of new indicates the first occurrence of an instance in the design process, and an index of old indicates any occurrence of the same instance after the first occurrence. This index plays an important role in observing the change and occurrence of linkages in four cognitive levels. An old instance most likely indicates the expertise stored in designers’ mind. The change of index demonstrates the change of experience including creation, modification, and reuse.

The class in DCOCS describes the categories and characteristics of an instance. These classes reveal the meaning of an instance. In the current coding scheme, P-instances have five classes and F-instances have six classes by no means they are exclusive lists, Table 1.

The content in DCOCS gives the semantic descriptions of the instance in the context of the design process. For example, the content of a P-instance indicates the visual elements by which a designer perceived this P-instance. The content presents the uncategorized data of an instance, and it provides the most detailed information of an instance.

3.7 Types

A type of an instance is determined by index, class, content, and dependency. For example, the type of Prn means the following. Firstly, the capital P stands for a P-instance. Secondly, small r describes the visuo-spatial relationship. Finally, the small n indicates that a new instance depending on new instances. The complex convention of defining the type listed six kinds of D-instance: Dc, Drf, Dsy, Dwo, Dts, and Dtd; eight kinds of P-instances: Psg, Posg, Pfn, Pfp, Pof, Prn, Prp, Por; and four kinds of F-instances: Fn, Fi, Fnp, Fop. In practice, this should be done by automatic formula provided by database software. The details of types settings for F-instances are given, Table 2.

Table 1 The classes of P-instances and F-instances in DCOCS

P-instance		F-instance	
Type of classes	Descriptions	Type of classes	Descriptions
Shape/texture/size	Perceiving shapes, lengths and textures of depictions	Function	Naming the visual elements
i-space	Perceiving the implicit spaces between depictions	Circulation	The movement and paths in a space
l-relationship	Perceiving proximity, alignment, intersection between depictions	Psych.reaction	Mental feeling about the visual performance and functionality
g-relationship	Global	Resource	Natural environment
v-relationship	Perceiving vertical relationship between depictions	View	What can be seen from a specific point
		Numerical info	Dimension and budgets

Table 2 The classes of types of F-instances in DCOCS

Fn	New meaning attaching to a new depiction	New		New
Frei	Re-interpreted function attaching to an old depict	New		At least one old
Fo	Old meaning attaching to an old depiction	Old		Old
Fi	Implementing old function in a new drawing	Old		At least one new
Fnp	A new function without drawings	New	No dependency	
Fop	An old function without drawings	Old	No dependency	

3.8 Dependency

Finally, relationships between different instances were determined. The instances in the higher levels may have dependencies on the low-level instances, and different segments are linked through visual-spatial relationship and semantics. The complex linkages in the encoded protocols reveal interesting design phenomenon that could not be explored by other kinds of research methodology. They are presented by baseon and triggerby in DCOCS. These linkages are different from that proposed in Goldschmidt (2001). The baseon and triggerby in DCOCS are the relationship between instances in a segment, while the linkages in Goldschmidt's research are the relationship between segments.

3.9 The Convention of Presenting the Encoded Results Using DCOCS

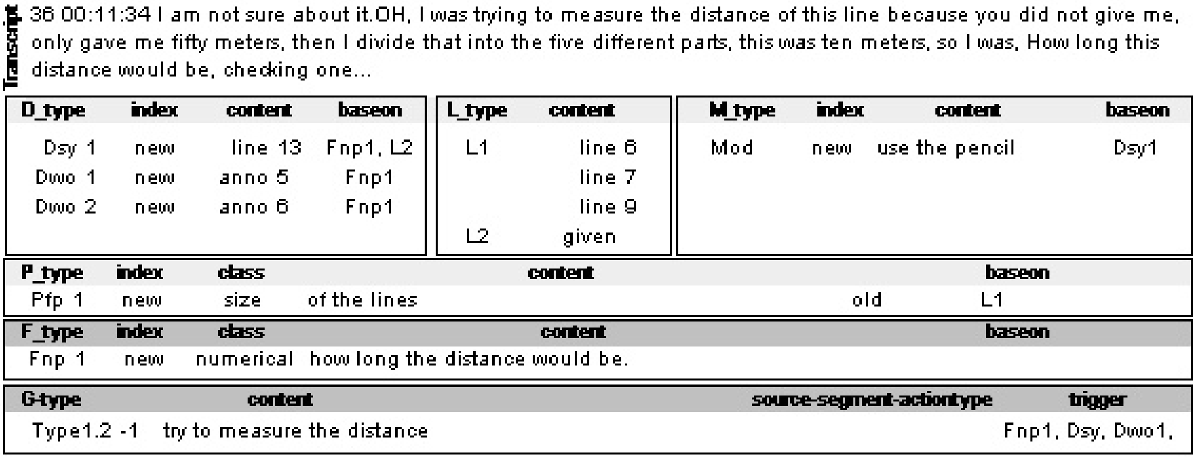
Encoding by DCOCS, a segment of a design episode is transformed into a series of encoded table in terms of levels, instances, class, index, and dependency. One encoded segment is represented to illustrate the complexity, Figure 4. The segment 36 starts at 00:11:34. The physical level has three D-instances and two L-instances, and one M-instance, perceptual level has one P-instance, functional level has one F-instance, and the conceptual level has one G-instance. All instances have type and content as the basic description of the instance. The relationship between instances is revealed through baseon; Dsy1 depended on Fnp1 and L2, and Dfp1 depends on L1. The index show the three D-instances, the P-instance, and the F-instance are new. The format of this encoding table was utilized in our researches.

4. Results and Discussions

Following the structure of DCOCS, different types of results could be obtained according to the levels researchers applied. Presented are the possible directions to use DCOCS. Four directions proposed are transcript-oriented, frequency-oriented, segment-oriented, and instance-oriented. To illustrate the potential, one of our verified encoded protocols is presented. The original data was given by an architectural expert with more than 25 years experience. The design brief was for a residential house. Details were given in terms of clients, sites, house, and required sizes of different spaces.

4.1 A Transcript-oriented View toward the Design Process

Both verbal and visual transcripts could be used in primitive protocol studies, such as the structure of the design process. The best example is the study of novel design decision and the E-D-T models by Akin (Akin, 1993). Moreover, the numbered depictions could be applied to form sketches-oriented research, such as the study of Do (Do, 2000).



36 00:11:34 I am not sure about it.OH, I was trying to measure the distance of this line because you did not give me, only gave me fifty meters, then I divide that into the five different parts, this was ten meters, so I was, How long this distance would be, checking one...

D_type	index	content	baseon
Dsy 1	new	line 13	Fnp1, L2
Dwo 1	new	anno 5	Fnp1
Dwo 2	new	anno 6	Fnp1

L_type	content
L1	line 6
	line 7
	line 9
L2	given

M_type	index	content	baseon
Mod	new	use the pencil	Dsy1

P_type	index	class	content		baseon
Pfp 1	new	size	of the lines	old	L1

F_type	index	class	content	baseon
Fnp 1	new	numerical	how long the distance would be.	

G-type	content	source-segment-actiontype	trigger
Type1.2 -1	try to measure the distance		Fnp1, Dsy, Dwo1,

Fig.4 The example of an encoded segment

4.2 A Frequency-oriented View toward the Design Process

The second kind of analyses is the descriptive statistics described the encoded representation of the design process. Segments, levels, instances, and types in DCOCS all could form a statistical description of the design process from a macroscopic view.

4.2.1 Segment

Divided by intentions, the subject encoded protocol consisted of 349 segments, Table 3. Each segment represented an independent thought. Therefore, we can estimate how many issues the expert handled and the degrees of richness in the intentions within the durations of 45 minutes.

4.2.2 Levels

There were four cognitive levels in DCOCS. The observed frequency of segments in which specific levels existed were calculated, Table4. We could find that conceptual levels did not always exist in the design process, indicating the time when the designer only sketched without specific thinking activities.

4.2.3 Instances

The five essential types of instances in DCOCS are D-instance, L-instance, P-instance, F-instance, and G-instance. The total numbers of them were calculated. These numbers were further divided by the total number of segments for the average, Table 5. The results showed that making functional references was very frequent activities in the design process. The functional and conceptual levels of DCOCS have the potential to reveal the characteristics of the information-processing of the conceptual design process. In contrast, the physical and perceptual levels of DCOCS have the potential to reveal the reflection-in-action of the design process, Table 5.

Table 3 The observed frequency of segments and average time span (seconds)

	Number of segments	Duration of experiment
Expert (EM01)	349	45 min

Table 4 The number of levels

	Number	Missing
Physical level	348	1
Perceptual level	321	28
Functional level	326	23
Conceptual level	242	107

Table 5 The total numbers and averaged numbers of different instances

	Total number	Averaged number
D-instance	422	1.2
L-instance	639	1.8
P-instance	624	1.9
F-instance	829	2.4
G-instance	240	0.69

4.2.4 Types

The observed frequencies of different types were calculated in terms of D-instances, L-instances, P-instances, F-instances, and G-instances, Table 6. These numbers give us the greater scrutiny of the design process. For example, the number of Prp and Por demonstrated the importance of the reviewing existing depictions.

4.3 A Segment-oriented View toward the Design Process

We examined further the design process from the viewpoint of segments that represent the intentions of subjects. Some interesting features of the design process could be found, such as speed of intention shift and the speed of occurrence of instances.

4.3.1 Speed of intention shift

Since segments represent for the participating designers' intentions, the speed of shifting between segments could represent the speed of thought in related to intentions. Of particular interest was the average time span per segment that was the speed of intention shift. In the expert's data, the speed was 7.7 seconds per segment, Table 7. It was calculated by using the number of segment and the duration of experiment that was 45.

It was noted that the speed were fast; this expert designer had intension-shift an every 8 seconds. This indicated intensive thinking process. Given that the speed we measured here represents the speed of thought or an episode of information-processing process, we speculated that the speed of the conceptual design process is faster than the remainder of the design process. Moreover, this phenomenon might also explain why designers prefer traditional pen and paper methods even when they have powerful and cutting-edge computers.

4.3.2 Speeds of physical, perceptual, functional, and conceptual instances

Further, the speeds of the different instances in the four cognitive levels of DCOCS were measured. The total number of instances of one type was divided by the total number of segments for the mean of observed frequency in a segment. Standard deviation (Std. Dev.) and maximum portrayed the distribution of the specific type of instances. Finally, the total experimental duration was divided by the total number of the instances of the measured type for average time. The subject had 3.2 physical, 1.8 perceptual, 2.4 functional, and 1.1 conceptual

Table 6 The observed frequency of types

D-instances		L-instances		P-instances		F-instances	
Dc	191	L1	313	Psg	31	Fn	243
Drf	40	L2	197	Posg	50	Frei	83
Dsy	49	L3	71	Pfn	46	Fi	107
Dtd	79	L4	22	Pfp	46	Fo	375
Dts	2	L5	7	Pof	28	Fnp	16
Dwo	61	L6	1	Prn	56	Fop	5
				Prp	248		
				Por	118		

Table 7 The numbers of segments and average time spans (s: second; m: minute)

	Number of segments	Duration of experiment	Average time span
Expert (SE01)	349	45m	7.7s

Table 8 Statistical Descriptions of different instances in terms of segments

EXPERT	Mean (observed frequency)	Std. Dev.	Maximum	Average Time (seconds)
D-instances	1.2	1.0	9	6.4
L-instances	1.8	1.2	6	4.2
Physical instances	3.2	1.6	13	2.4
Perceptual instances	1.8	1.1	6	4.3
Functional instances	2.4	1.6	7	3.3
Conceptual instances	1.1	1.0	4	7.0

instances for every segment on average, Table8. In terms of physical instances that include D-instances, L-instances, and other physical instances, there was a new instance every 2.4 seconds in the expert's case. The numbers of L-instances were the main factors. The average time of D-instances was very fast, and this speeds was fast enough to catch up with the speeds of intention shift.

These different speeds were measured when the designers were using pen and paper. Not only did the average numbers of all instances emphasize the speeds of the conceptual design process, but it also highlighted the rich information-processing process during the conceptual design process. The actually numbers of these calculations are not important but rather their relative magnitudes. For example, it would be interesting to compare the speed of D-instance when designers use pen and paper to that when using CAD. They should not be treated as universal numbers.

4.4 An instance-oriented view toward the design process

Finally, the detailed structure of DCOCS enables us to conduct instances-oriented studies of designing. We could examine different kinds of instances under scrutiny, especially the relationship between different kinds of instances. The best example is the studies of unexpected discoveries and re-interpretation proposed by Suwa (Suwa et al., 2000). The index, type, and dependency of P-instances were utilized to highlight the connections between cognitive events and creativity. There are still many interesting issues unfolded under the framework of instances. These analyzed results, however, could not be obtained by other methods, such as observation or interview.

5. Conclusions

This paper described the methodology and the experiments of DCOCS. The details of analytical process presented the definitions and structure of DCOCS. The anatomy of the design process was presented by segments, levels, and instances. The characteristics of the design process were described by types, index, class, content, and the dependency of DCOCS. The design process was examined from transcript-oriented, frequency-oriented, segment-oriented, and instance-oriented viewpoints. The establishment of DCOCS is not the end of our design protocol research, but a beginning of a long road to understand the cognitive behaviors of designers. Given the complexity and ambiguity of the design process, more design studies under the same analytical framework should be done to verify our interesting findings and to form our better comprehension of designing.

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