WHAT ARCHITECTS AND STUDENTS SEE IN ARCHITECTURAL DESIGN SKETCHES: A PROTOCOL ANALYSIS

MASAKI SUWA[1] and BARBARA TVERSKY[2]
[1] Advanced Research Laboratory, Hitachi Ltd. 2520, Hatoyama, Saitama 350-03 Japan.
[2] Department of Psychology, Stanford University, Stanford CA 94305, USA.

Abstract The present research aims at examining what information architects think of and read off from their own freehand sketches, and at revealing how they perceptually interact with and benefit from sketches. We explored this in a protocol analysis of retrospective reports; each participant worked on an architectural design task while drawing freehand sketches, and later reported what she/he had been thinking of during the design task. This research lies within the scope of examinations of why freehand sketches as external representation are essential for crystallizing design ideas in early design processes.

External representations such as diagrams, sketches, charts, graphs, and even hand-written memos not only serve as memory aids, but also facilitate and constrain inference, problem-solving and understanding. Geometry diagrams in theorem-proving tasks, for example, guide solvers to explore only visually plausible inference paths[1], facilitate retrieval of perceptual-chunks that are useful for constructing efficient proofs[2,3], and provide visual cues for extracting new chunks from the current problem and assimilating them for future use[4]. Petre[5] showed that good use of graphical representations in programming environments, i.e. what she calls 'secondary notation' of graphics, prevents programmers from mis-cueing and mis-understanding. Larkin and Simon[6] enumerated general features of diagrammatic representation by which human problem-solving is facilitated, providing a list of how facilitation tends to occur. Tversky discussed how people use space for conveying meanings and abstract concepts, drawing on examples from ancient depictions and children's early drawing[7] as well as from comtemporary charts, graphs and diagrams[8].

Facilitation by external representation derives, not just from its external existence but from the interaction between the representation and the cognitive processes of interpreting it[9]. Architects' sketches are a tool for this sort of interaction as well[10,11]. Architects put ideas down on paper and inspect them. As they inspect their own sketches, they see unanticipated relations and features that suggest ways to refine and revise ideas. This cycle -- sketch, inspect, revise -- is like having a conversation with one's self12. Goldschmidt13 conjectured that sketches give access to various mental images, figural or conceptual, that may potentially trigger ideas in the current design problem. Further, she claimed that visual design thinking is a rational mode of reasoning as well, although it has been set aside behind the dominant paradigm of linguistic, logical reasoning in cognitive science14. This claim perfectly coincides with a growing enthusiasm for diagrammatic reasoning in cognitive science, especially groups of researchers who claim that visual information is valid for reasoning and that visual reasoning has its own sound logic15,16, just as conventional sentential reasoning does.

Why are sketches a good medium for reflective conversation with one's own ideas and imagery? This general question can be reduced to more precise issues to be addressed. One is an issue of what aspects or features of sketches themselves as external representations allow for reflective conversation, an issue addressed by Goel17. He found that because freehand sketches in the early design process are "dense" and "ambiguous" in Goodman's18 sense, they work well for crystallizing design ideas. Another is an issue of what kinds of interaction architects have with their own sketches. This issue can, in turn, be reduced into a couple of issues; "how do they see sketches?", "what do they see in sketches?", and "how and what do they draw?". Goldschmidt's work13 pertains to the first category. She observed that there are two ways of inspecting sketches, i.e. "seeing as" and "seeing that", and that the former is an especially powerful means for what she calls interactive imagery. Van Sommers's work19 looked at graphic production from a developmental and cognitive perspective, and hence pertains to the third category. The present paper addresses the second issue, "what architects see", by focusing more precisely than the past work on the contents of information categories that architects "see" in their own sketches. The purpose of the present paper is to analyze how those different types of information intermingle with each other in their design thoughts, and to reveal how practicing architects differ from students in it.

We brought these phenomena into the laboratory in a protocol analysis of retrospective reports of subjects' design thoughts. The most typical method for analyzing subjects' cognitive processes is, and has been, concurrent thinking-aloud verbal reports20,21. We did not employ it because talking aloud may adversely interfere with participants' perceptions during their sketching activities22. This issue is discussed in more detailed in Section 5.1.

Another purpose of this study is to explore implications for ways that future design tools, especially sketching tools, assist designers/architects. Many researchers17,23,24 claim that the currently available computational tools do not support naive freehand sketching processes in the early design phases. This is because they are intended for visualizing, comparing, testing and implementing the design ideas that have been already obtained in earlier design processes, not for supporting the very processes in which design ideas occur. Several projects[23,24,25] on pen-based sketch tools have recently addressed this problem. We believe that the present research will be able to provide important implications for more endeavors. This issue is discussed in Section 6.3.

1. Experimental Design

The experiment consisted of two tasks, a design task and a report task. Two practicing architects and seven advanced students in an architectural department participated. In the design task, each participant worked on designing an art museum through successive sketches for 45 minutes. They were provided with a simple diagram representing an outline of the site, in which they were supposed to arrange not only a museum building but also a sculpture garden, a pond, a green area, and a parking lot. The building was required to have entrance(s), a ticket office(s), display rooms for about 100 paintings, a cafeteria, and a gift shop. Participants were supposed to use freehand sketches as a tool for designing. They were not asked to report concurrently what was going on in their minds, nor were they interrupted by the experimenter during the design task. Their sketching activity was videotaped.

Following the design task was the report task. While watching their own videotape, participants were asked to remember and report what they were thinking as they drew each portion of each sketch. In case their reports lagged behind the videotape, they were allowed to stop the tape until reporting all that they remembered about the current topics. Therefore, the duration of the report task depended on the participant, varying from one hour to one hour and fifteen minutes. Participants were not interrupted with questions during the report, except for following cases; when they obviously skipped reporting about certain portions of their sketching activity, then they were requested by the experimenter to rewind the videotape and report those portions. We recorded the participants' voices as well as videotaped the screen itself on which not only their sketching activity in the design task but also their pointing gestures in the report task showed up.

2 Information Categories

In interpreting the data, the first step was to determine a set of information categories into which the contents of participants' protocols could be fit. Table 1 shows the four major categories and their subclasses. We derived the four categories from theoretical discussions and historical evidence on how external representations convey meanings and concepts, from past literature on design processes that suggest what architects generally think of in design process, and from intensive study of the protocols. Many theorists like Larkin and Simon[6] and Tversky[7] have suggested that the pictorial devices for expressing meanings and concepts consist of (a) depicted elements, whether objects, spaces or icons, and (b) spatial arrangement of them. They have also suggested that spatial arrangements have the ability to express not only literal spatial relations but also abstract or conceptual relations. From these discussions, it would be safe to conjecture that at least three information categories should be proposed, i.e. depicted elements, spatial relations, and abstract relations.

Depicted elements are sometimes intentionally drawn and thus possess explicit shapes and sizes, but sometimes they are embedded as partial elements or implicit objects and emerge to the viewer's eyes only when he/she discovers a new way of restructuring the whole configuration that includes those elements[26]. Larkin and Simon[6] and Koedinger and Anderson[3] referred to this property of diagrams as "emergent properties". Therefore, we chose to name the first category as "emergent properties", instead of just depicted elements. "Spatial relations" hold among these depicted elements, and are inherently visual features in the sense that architects/designers can see them in their own sketches, just as emergent properties are also visual. In the domain of architectural design, abstract relations typically correspond to "functional relations". Forms and functions are the two major concepts in the domain that are conceptually distinct and yet intertwined with each other[27]. Functional relations in this domain denote interactions among spaces, things, people visiting or using them, and/or environments. Unlike emergent properties and spatial relations, functional relations are inherently non-visual aspects of architectural designs.

Table 1: Information categories and their subclasses

Major Category	Subclasses	Examples of Phrases in Protocols as Evidence
Emergent Properties	spaces	"areas", "places"
	things	descriptions or names of something
	shapes/angles	"round", "prolonged", "wavy line", "too sharp a corner"
	sizes	"big", "tiny", "narrow"
Spatial Relations	local relation	"adjacent", "far", "connected", "lined up"
	global relation	"symmetrical", "configuration", "axis"

Functional
   Relations
practical roles
abstract features/reactions
views
lights
circulation of people/cars
"a ticket office should be close to an entrance.."
"waves/forces (from this shape)", "good show to visitors"
"view line", "the appearance (of this building)"
"(this place is always) bright, having sunshine"
"people meander through (this narrow space)"

Background Knowledge

"post/beam structures", "An important thing in an urban setting is..."

In addition to the above three categories, we established a fourth one, i.e. "background knowledge", because the past history of studies on cognitive science has indicated that every cognitive task performed by human beings is mediated by background knowledge about the domain to which the task belongs. Background knowledge in the domain of architectural design includes (a) domain knowledge about structures and materials for fulfilling certain functions and spatial arrangements, (b) standards for doing the esthetic and preferential evaluations for their own design decisions, and (c) knowledge about the relevance and the influence of the architectural designs to/from the social contexts and the environments in which the architecture is built.

The subclasses of each category were enumerated as a result of investigation of all the protocols. For emergent properties, in cases where participants discovered or created certain areas for something or some functions, or referred to already depicted (e.g. encircled) areas, we encoded the evidence as spaces. In cases where subjects depicted things, referred to already depicted things, or even observed that things which were not actually there emerged by the appearance of other surrounding depictions, we encoded the evidence as things. Shapes/angles denote the shapes of things or spaces, or the angles which line drawings stand against some other items or line drawings. Sizes denote the size of things or spaces. The latter two are visual attributes of the former two. These four subclasses constitute emergent properties.

Spatial relations were subdivided into two classes, local relations and global relations. Local relations include (a) adjacency, (b) remoteness, (c) physical connectedness by mediation of other things, and (d) alignment, which hold between two or more different spaces or things. Global relations include (e) a configuration of spaces or things within the whole site or a certain area in it, (f) symmetry of spaces or things, and (g) axes, or a sense of direction which spaces or things inherently possess.

Functional relations were subdivided into five categories. Practical roles denote semantic relevance, conflict, separateness among practical roles of spaces or things. This is a subclass concerning how people use them. Abstract features/reactions include interrelations among the abstract features of spaces or things, as well as interactions and feelings which people may have from experiencing spaces or things. This is a subclass concerning how people react to them. The other three subclasses are more specific types of interactions between people, spaces and/or things, which are typical in architectural design. Views include the actual appearance of spaces or things imagined by participants, and the visibility of a space to and from another space within the site. Lights denote interactions between depicted elements and sunlight. Circulation of people/cars is an encoding of participants' report about people/cars moving around within or outside the site.

We did not divide background knwoledge into subclasses, because the precise distinction of what types of knowledge participants refer to is not relevant to the present research.

3 Protocol Analysis

3.1 ENCODING INTO INFORMATION CATEGORIES

For each participant, we first encoded all the information in the verbal protocols into the subclasses of information categories. Basically, verbal protocols were the main target of our analysis; we picked up words, phrases and sentences as evidence of each subclass of information categories. For supplemental purposes, we employed the visual data of videotapes which had recorded their pointing gestures in reporting, in two ways. First, because verbal reports tended to contain lots of abbreviations and ambiguous pronouns, the participant's pointing gestures helped to clarify these. Second, participants sometimes missed reporting about certain depictions that were actually recognized in their sketching activities. Visual data showed what depictions were not reported about. In this case, we encoded that some "unknown" thoughts were actually there.

Table 2 illustrates a portion of a protocol of a practicing architect, for about 3 minutes from nine minutes after the beginning of the design task. When we encoded raw protocols, it was necessary to augment ambiguous phrases with interpretations. We did this by seeking justifications. One kind of justification was to know which areas or depictions the participant was talking about from his/her gestures of pointing to the screen while reporting. Another kind was to interpret phrases or pronouns from contextual, pragmatic, and semantic information. [p: ..] corresponds to the former, and [s: ..] to the latter. In the right column, the encoded subclasses and the phrases for which we encoded are listed.

We did not encode such evidence that participants talked about their goals or intentions for future actions, because goals or intentions are not what participants see in their sketches, but rather represent meta-level control over their cognitive processes. A typical example is seen in the segment 43 in Table 2, i.e. "yes, don't forget this".

3.2 SEGMENTATION

Then, we divided the entire encoded protocol into segments. A segment, whether consisting of one sentence or many, is defined as one coherent statement about a single item/space/topic. If a participant explored more than one statement about an item/space/topic, they were regarded as different segments. For example, see the portion of segments 42 and 43 in Table 2. This portion includes statements about a "tension" between two areas, but should be divided into two segments as such. In Segment 42, he devised a notion of "tension", suggesting its importance in a surburban setting. Then, in Segment 43, he explored the idea by placing water or sculpture elements in one of the two areas.

Even if participants missed reporting about a certain depiction which was actually recognized in the videotape, the depiction should stand for a segment, because we are sure that some design thoughts had been actually there.

A segment usually included several information subclasses, and an entire protocol for a participant typically consisted of hundreds of segments.

Although we devised the notion of "segments" independently, we learned afterwards that Goldschmidt13 had already proposed a similar way of decomposing design processes into small units, "design moves" and "arguments". According to her definition, a design move is "an act of reasoning which presents a coherent proposition pertaining to an entity that is being designed", and arguments are "the smallest sensible statements which go into the making of a move" (p.125). This definition and the examples shown suggest that a segment in our notion corresponds to a design move in its granularity.

3.3 CONCEPTUAL DEPENDENCY AMONG SEGMENTS: TWO TYPES OF SEGMENTS

Then, we analyzed conceptual dependency among segments. We define that a segment has a conceptual dependency (CD) from a past segment, whether immediately preceding or anywhere in past, when (a) the item/space/topic in the current segment derives from its relationship with another item/space/topic which the past segment was concerned about, or (b) the current segment explores the same item/space/topic which the past segment was concerned about, or (c) a design idea or a constraint established in the past segment has been generalized and is applied to the current segment.

As a result of this analysis, we found that the entire design process includes many blocks of contiguous segments. We call each block a "dependency chunk". We call segments which stand alone, not forming a chunk with others, "isolated segments". The contiguous segments that should form a dependency-chunk are determined such that, for each chunk, every constituting segment except for the first segment of the chunk has a CD from at least one of the preceding segments of the chunk, whether or not immediately preceding. The first segment does not have a CD from its immediately preceding segment ("segment P") nor from any segments in the dependency-chunk, if any, to which "segment P" belongs.

Figure 1: A schematic representation of segments, conceptual dependency links, and dependency chunks

A dependency chunk stands for a sequence of conceptually interrelated design thoughts, each of which was evoked in relation to preceding thoughts in the chunk. For example, suppose that a participant designed an entrance of the museum building, and then turned to design a ticket office, and a gift shop. If the participant designed the ticket office and the gift shop, considering that a ticket office should be practically located near the entrance, and a gift shop should be located near the entrance/exit for allowing visitors to browse around just before going home, then this sequence of design thoughts should form a dependency chunk.

Figure 1 is a schematic representation of a configuration of segments, conceptual dependency links and dependency-chunks, for the portion of the protocols of Table 2. Each rectangle node represents a segment, and each link between two nodes a CD. The numbers written beside nodes correspondto the segment numbers. Segments are depicted from the left in the order of their occurrence. The segments forming a dependency chunk are depicted in the same vertical level.

The first segment of a dependency chunk and an isolated segment indicated that the participant's focus of attention departed from the preceding thoughts and moved to another item/space/topic. We classified such a segment as a "focus-shift" segment. It corresponds to the gray nodes in Fig.1. Each focus-shift segment is depicted such that it is displaced lower than its immediately previous segment. We call all the other segments, each of which belongs to a dependency chunk but is not the first segment within the chunk, "continuing segments". In a continuing segment, the participant keeps exploring a topic which is conceptually related to the past segment(s) within the same chunk. It corresponds to the white nodes in Fig.1.

A central tenet of this research is that architects' acts of shifting focus of attention in an opportunistic way and their acts of exploring related topics consecutively are the two important constituents of their design activity. This view derived from our notion of dependency chunks. Shifts of focus allow for a lateral variety of design topics/ideas, and a sequence of related thoughts allows for detailed, deep exploration of design ideas. The former corresponds to what Goel calls "lateral transformation," and the latter to what he calls "vertical transformation"17.

4 Results

4.1 OBSERVATIONS ABOUT THE DESIGN PROCESS

Table 3 shows the percentage of continuing segments and focus-shift segments for the average of students and for the two architects. Architects have remarkably more continuing segments than students. Table 4 shows the total number of dependency chunks, the number of dependency chunks whose length is 2, and the number of dependency chunks whose length is more than 2. Architects have many more dependency chunks than students. Importantly, this difference comes mainly from the number of chunks whose length is more than 2, while the number of chunks whose length is 2 does not differ greatly between architects and students. These results, that architects have more and longer dependency chunks than students, indicate that once architects shifted their focus of attention, they thought more deeply about the topic. What causes this difference? We believe it occurs because architects are able to "read-off" more different types of information from their sketches. In the following section, we will discuss what types of information are "read" by architects and students in each of focus-shift segments and continuing segments.

Table 3: The percentages of both types of segments in
Table 4: The number of dependency chunks for students and
protocols of students and architects
architects

Segment types
Students (%)
(aver. ± std.)
Architect 1
(%)
Architect 2
(%)

Kinds of depend-
ency chunks
Students
(aver. ± std.)
Architect 1
Architect 2

continuing

35.2 ± 4.2
49.2
46.8

two in length
13.7 ± 4.0
18
16

focus-shift
64.8 ± 4.2
50.8
53.2

more than two
12.6 ± 2.7
39
19

total
100
100
100

total number
26.3 ± 3.8
57
35

4.2 INFORMATION CATEGORIES IN BOTH TYPES OF SEGMENTS

Table 5 displays the percentages of each type of information for focus shift and continuing segments for architects and students. There were both striking similarities and differences between architects and students in their interpretations of their sketches. For both, the predominant information in focus shift segments was spaces, whereas the predominant information in continuing segments was local spatial relations. This means that finding spaces was the major impetus for shifting focus to a new part of a sketch whereas examination of local spatial relations was the stimulus for continued consideration of related topics.

Table 5: Distribution of Information Categories in Protocols of Students and Architects by Segment Type

Focus-shift segments

Continuing segments

Subclasses of information
category
students
aver.±std.
archi-tect1
archi-
tect2
students
aver.±std.
archi-tect1
archi-
tect2

spaces
30.8±0.7
28.1
24.6
19.8±4.1
19.6
16.0

things
6.1±3.8
2.3
4.6
4.1±2.5
4.5
3.7

shapes/angles
6.2±2.4
8.7
10.9
8.4±2.9
5.3
4.9

sizes
2.9±1.3
5.0
5.7
3.3±2.0
1.9
4.3

global spatial relations
7.5±3.4
6.0
4.0

6.3±2.5
4.8
5.5

local spatial relations
13.9±2.1
11.8
14.3
20.2±3.2
19.1
19.0

practical roles
5.1±1.9
1.9
4.6
8.6±2.6
4.5
8.6

abstract features/reactions
2.9±1.6
3.8
6.8
4.7±1.5
7.9
6.8

views
5.6±2.1
8.3
8.0
5.4±2.3
9.3
6.7

lights
1.5±1.3
4.4
1.7
1.0±1.1
4.3
0.6

circulation of cars/people
9.4±2.9
9.8
5.7
8.1±1.8
13.8
9.2

background knowledge
8.1±2.0
9.9
9.1
10.1±2.2
5.0
14.7

total
100
100
100
100
100
100

Note: Categories in which architects had a significantly higher percentage of responses than students are highlighted.

As for differences, the highlighted portions of the table indicate significant differences between architects and students. In focus-shift segments, both architects considered shapes/angles, sizes, views more than students. This means that architects, in contrast to students, began thinking about visual attributes of depictions and views, as soon as they shifted attention to a new part of a sketch. In contrast, in continuing segments, architects differed from students only in the consideration of all the functional relations except practical roles. This means that architects continued to interpret functional relations, especially abstract features/reactions, more frequently than students as their thinking progressed within a dependency chunk. It should also be noted that only "practical roles" was completely different in nature from all the other functional relations. Architects thought of practical roles of spaces/things and their relations equally or less frequently than students.

These results may be summarized by the following insights, which might be adopted as useful strategies to follow in designing. First, because architects are trained to, and thus able to, think of shapes/angles and sizes, which are inherently visual attributes of depicted elements (spaces and items/things), just after they shift focus to a new item, space, or topic, their focus shifts won't end in vain. Second, because architects are able to explore many more functional considerations, especially abstract features/reactions, in the continuing segments, they can pursue design thoughts more deeply within and across dependency chunks than students. This analysis has revealed that sketches stimulate thinking about not only perceptual relations but also about inherently non-visual functional relations to both advanced design students and practicing architects. Practicing architects are even more adept at reading-off functional issues from perception of visual features than students of architecture.

5 Related Work and Discussion

5.1 THINK-ALOUD PROTOCOLS vs. RETROSPECTIVE PROTOCOLS

The analysis of think-aloud protocols has been a major method for seeking insights into human thought processes in complex cognitive tasks20. It has been employed extensively in studies of design activities as well. We did not, however, employ the think-aloud protocol method because previous work suggested that talking aloud concurrently may interfere with participants' perception during their sketching activities20,22. This effect would undermine our experiment, because our purpose was to reveal the perceptual interactions between a designer and his own sketches.

Instead, we chose to employ the method of retrospective reporting. However, another undesirable effect, called selective recall, is inevitable in this method20. Participants may tend to selectively report what is relevant to the retrieval cues given in the reporting task and/or what is relevant to their purposes and intentions while reporting, neglecting other thoughts which must have occurred during the earlier cognitive tasks. The measure we took for alleviating this was to add memory cues to the retrospective reporting sessions in the form of showing each participant the videotape of his/her own sketching behaviors. This provides the participant with the visual cues about the exact sequence of sketching, including the timing, hesitations, returns, and redrawings. Those visual cues were expected to help each participant remember what he/she thought, relevant or irrelevant.

5.2 FORMAL ANALYSIS vs. INFORMAL ANALYSIS

Past work on protocol analysis for design process has taken one of two approaches, formal analysis and informal analysis. In formal protocol analysis, design is seen as a rational problem-solving search process through a 'solution space'28,29,30,31,32. Its main focus is to describe design in terms of a general taxonomy of problem-solving, i.e. problem states, operators, plans, goals, strategies and so on, and thus to come up with generalizable findings on design methodology. In informal analysis, on the other hand, design is seen as a process in which each designer "constructs his/her own reality" by his/her own actions that are reflective, responsive and opportunistic to the design situation, as Dorst & Dijkhuis33 characterized it. Schon's work on "designer as a reflective practitioner"34 and Goldschmidt's work on the design cycle of "seeing-as" and "seeing-that"13 are typical examples of this category. The present work belongs to the latter approach in the sense that we see the design process as composed of cycles of focus shifts and continuing thoughts, and that we aim at revealing how each small cycle will be driven by designers' actions of seeing different information categories.

In comparing the present research with Goldschmidt's, the development of a precise set of information categories is essential; the present research has contributed, and is expected to contribute, to classifying "seeing-as" phenomena into distinct types. For example, architects tend to unintentionally discover certain "spaces" and "things", two basic visual elements in architectural sketches, from a configuration of unexpected line drawings. Sometimes, functional issues such as "abstract features and reactions" emerge to their eyes from the visual attributes of depictions such as "shapes/angles" and "sizes", and/or from the "spatial arrangements" of depicted elements.

5.3 THE LINK BETWEEN DESIGN PROCESS AND THE CONTENT OF DESIGN PROBLEM

Dorst and Dijkhuis33 argued that the analyses of design processes should focus on both "design processes" and "the contents of the design problem", in order to arrive at generalizable insights on what good and healthy design activities are. What they mean by "analyzing design processes" is to reveal general tendencies and features of how design processes are structured. What they mean by "analyzing contents" is to reveal what information, resources, and knowledge are involved there. Dorst and Dijkhuis pointed out that the formal "rational problem-solving" approach focuses only on process components of design activities, and fails to analyze the contents of what designers see and think and what knowledge they use. On the other hand, case studies pertaining to the informal approach, typically Schon's reflection-in-action theory, are content-oriented and thus difficult to compare and to use to elicit generalizable insights on good ways of doing designs. Dorst and Dijkhuis concluded in the end that the informal approach should be further developed, by "building a taxonomy of design problems, and of frames" (p. 274).

Our approach addresses precisely this issue. The set of information categories and their subclasses can be seen as a taxonomy of the content component of design problems. This categorization is general enough to be applicable to different design activities, because it was derived from the perspective of cognitive science, that is, from general insights about how people see, think, and perform, perceptually and conceptually. On the other hand, the two types of segments, focus-shift and continuing segments, are the process components of design activities. The analysis we have developed explores the link between process components and content components, by revealing what information categories are dominant in and characteristic of both types of segments.

5.4 CHUNKS IN DESIGN PROCESS

Recently there has been a growing belief in the field of architectural design that a fruitful way of analyzing a design process is to decompose the entire process into its smallest components and to focus on the interlinks among these components. Our notion of "dependency-chunks" falls into this category, and thus it is not new in itself. The term "chunk" was coined by Miller[35] to describe subjective grouping of unrelated items. It was adopted by researchers studying problem solving and reasoning to characterize experts' knowledge[3,4,36]. Experts are able to organize elements that seem unrelated to a novice into cohesive units.

These ideas have been more recently adopted by researchers studying the design process. Out of several predecessors who have used this approach, Goldschmidt's work on "linkograph"[37] is the most similar to ours. Her work is a forerunner of ours in the sense that we share her view that analyzing interconnectivity among segments will yield insights about what design process leads to good productivity. However, her notion of "chunk" differs from ours in granularity. A chunk in her notion takes the form of a pattern of links that circumscribes a large number of design moves in it, typically more than ten, so that there are few, or none at all, links across different chunks. In contrast, our chunk is configured from a relatively smaller number of segments. This difference is brought about by the difference in purposes of what analyses of chunks are for. Goldschmidt aims at revealing a geometrically discernible pattern of interconnectivity of design moves, i.e. the relatively global structure of a design process. On the other hand, we aimed at revealing smaller cycles of design processes, which are characterized by focus-shift and continuing segments. The smaller granularity of our chunks is suitable for this purpose.

5.5 DESIGN THOUGHTS ON FORM AND FUNCTION

Arnheim[27] insisted that the visual form and the function of architecture are physically and psychologically intertwined with each other, and that exploring psychological aspects of visual forms should help architects understand the interplay between form and function. Consider, for example, an architect's depiction of several visual objects, for example, the contours of buildings, in a plan drawing. Arnheim observed that not only their visual shapes emerge up in front ("figures") to the eyes of the architect, but also the interspaces among these figures ("ground") can be, and often are, emergent objects in its own right. This is because, Arnheim surmised, architects are able to sense invisible forces issuing from the visual forms of the depicted objects and from the interspaces, and to perceive the interplay of those counterbalancing forces from two sources (Chapter 3).

Here, note that invisible forces and their interplay are demystified and can be interpreted as functional thoughts which derive from visual shapes. In terms of our categorization, visual forms correspond to spaces, things, shapes/angles, sizes, and their spatial relations, local or global. And invisible forces and their interplay correspond to abstract features and reactions.

Viewed this way, our findings corroborate his claim. Architects, more often than students, attend to shapes/angles and sizes, the visual attributes of depicted elements, just after they have shifted their focus to new thoughts. We may interpret this phenomenon as evidence that practicing architects know better that visual attributes are good sources from which to derive design thoughts on functions. In fact, our finding suggests that architects, when they are exploring related thoughts successively, are better than students at reading-off non-visual functional issues, especially abstract features and reactions, from visual features on sketches.

6. Future Work

6.1 THE CAUSES OF FOCUS-SHIFT AND EXPLORATION OF RELATED THOUGHTS

The present research suggests that shift of focus and exploration of successive related thoughts are two important vehicles for pushing forward design processes. In this paper, we examined statistical correlation between the segment types and the information categories characteristic of them. This is a rather rough examination, just the dominant information categories in each of the two segments. It did not take a close look at what are the reasons or causes of focus-shift and exploration. Visual cues that can potentially be the causes are shapes/angles, sizes, textures, line attributes of depicted elements, and proximity, connectivity, continuity/alignment, comparison of more than one elements, and so on. These cues are obtained by dividing the current information subclasses more precisely at a finer grain. Examining the visual cues that are involved with each evidence of focus-shifts and explorations in protocols is one of our future work.

6.2 THE ROLES OF EXTERNAL REPRESENTATION

The present research concluded that sketches allow architects to "read-off" non-visual functional issues from visual features. So, what nature of sketches as external representation enables and facilitates the act of "reading-off"? Is it because sketches are visual and thus certain configuration of line drawings will visually cue the architect's background knowledge about functional issues, that "reading-off" is possible? Or, is it because sketches are more or less specific in Stenning & Oberlander's sense16 and thus a spatial relation between things that have been drawn on the sketch irrelevantly to each other becomes emergent all of a sudden, suggesting a certain functional issue? Or, is it because freehand sketches are ambiguous in Goel's sense17 and thus it affords re-interpretation of line drawings? A close look at each evidence of "reading-off" phenomena in protocols from a viewpoint of the nature of sketches involved is another future work. This line of study on architectural design sketches lies within the scope of a broader issue; why and how external representation is essential for people's problem-solving and concept-forming

6.3 IMPLICATIONS FOR DESIGN TOOLS

Due to the inflexibility of conventional design tools mentioned earlier, designers and architects still turn to freehand sketches for naive concept-forming. So, how should a design tool assist designers in early design processes? What implications have been brought to us by the present research?

This study implies that perception of visual attributes of sketched items, e.g. sizes and shapes/angles, plays an important role in exploring inherently non-visual functional thoughts, one important goal of a design process. In other words, sketches serve as a "perceptual interface" through which one can discover non-visual functional issues behind the visual features. This has motivated us to aim at a computational sketching tool that possesses the functionality of enriching perception38. If a computational sketching tool can encourage users to respond to visual features in sketches and to "read-off" what they suggest, novice designers may improve their ability to use sketches as "perceptual interfaces". Even practicing architects may find it stimulating the discovery of new ways to look at their own sketches that they would otherwise not notice. It can provide users with enriched interactivity, motivate them to use the tool, and enable them to engage in their task productively.

Our vision is of a tool that will, when a user draws a new figure, present visual stimuli, such as "animation" or "highlighting" of sketched items (as "figure") as well as of interspaces among the items (as "ground")39. The basic concept is that if the look of visual features of items (such as shapes, angles, sizes, textures, and line-features) and of patterns produced by their spatial arrangement fluctuates, then the fluctuation may encourage the user to "read-off", beyond just their visual features, their potential appeal to perception in unanticipated ways. Which items and interspaces should be candidates foranimation and highlighting? How should animation and highlighting be performed? That's the immediate future issues to be addressed.

The functionality of "enriching perception" is orthogonal from the criteria that past literature on computational sketching tools have proposed. Gross's Cocktail Napkin25 has proposed a scheme of on-line access to peripheral information such as past inventories of design sketches, either public or personal. This allows computational sketching to be "useful" in early conceptual design phases. Kramer pointed out that, when architects make sketches on paper, they dynamically associate sketched marks with meanings, structures, and operations only when the association is needed, not when the marks are put down. He proposed an infrastructure named translucent patches 24 in order to providing users with the freedom of dynamic and fluid associations. This allows computational sketching to be "natural", free from unnatural constraints that conventional design tools would impose.

7 Conclusions

We have examined participants' design thoughts in an architectural design task, by the method of retrospective protocol analyses. One of the main goals was the development of a set of information categories into which the contents of participants' protocols can be fit. We devised this from the perspective of cognitive science, especially the research on diagrammatic reasoning. Another goal was the way of decomposing the entire protocol of a participant into segments, and of analyzing the structure of dependency links among segments, that is, dependency chunks. Our definitions of dependency links and chunks yielded an analysis of protocols with appropriate granularity which allowed us to conclude that the design process consists of smaller cycles of focus shift and continuing thoughts on related topics. Our finding, that architects had more and longer dependency chunks than students, indicates that once architects shifted their focus of attention, they thought more deeply about the topic.

Another contribution of the present research is the investigation of the information categories that are dominant in or characteristic of each of focus-shift segments and continuing segments. We found that because architects are more able to think of shapes/angles and sizes, which are inherently visual attributes of depictions, just after they shift focus to a new item, space, or topic, their focus shifts are more productive. Moreover, we found that because architects are capable to "read-off" many more functional relations in continuing segments, especially abstract features and reactions, from perceptions of depicted elements, they can pursue design thoughts more deeply within and across dependency chunks.

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