How do designers shift their focus of attention in their own sketches?

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Abstract

External representations serve as visual aids for problem-solving and creative thinking. Past research has enumerated some of the features of external representations that enable this facilitation. We have questioned how and why architectural design sketches facilitate exploration of design ideas, by conducting protocol analyses of designers' reflections on their own sketching behavior. Our previous analyses of their protocols revealed that skilled designers, once they shift attention to a new part of a sketch, are able to explore related thoughts more extensively than novice designers. How do they keep focused on related thoughts? What are the driving forces for successive exploration? We examined the types of information that expert and novice designers considered during and between chunks of related thoughts. We found that focus shifts driven by consideration of information about spatial relations led to successful exploration of related thoughts. We relate these results to some aspects of facilitation by the externality of sketches.

Introduction

Characteristics of External Representations

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. A geometry diagram in theorem-proving tasks is a typical example; it highlights plausible inference paths (Gelernter 1963), visually cues necessary knowledge structure (McDougal and Hammond 1992; Koedinger and Anderson 1990), and constrains assimilation of new knowledge (Suwa and Motoda 1994). Petre (1995) showed that good use of graphical representations in programming environments prevents programmers from mis-cueing and mis-understanding. Architectural sketches as well, the topic in this paper, serve as visual aids for design thinking in many ways (Laseau 1989). Architects put ideas down on paper and inspect them. As they inspect their own sketches, they discover visual cues that suggest ways to refine and revise ideas. This cycle -- sketch, inspect, revise -- is like having a conversation with one's self (Schon and Wiggins 1992).

How does the externality and visibility of representations facilitate problem-solving and creative endeavors? A number of scholars have provided insights on the facilitatory value of external representations (e.g., Clement 1994; Cox and Brna 1995; Goel 1995; Goldschmidt 1991; Kirsh 1995; Larkin and Simon 1987; Petre 1995; Stenning and Oberlander 1995; Suwa and Tversky in press; Tversky 1995a, 1995b). Our own analysis and the research at hand lead us to highlight three functions of external representations. First, externalizations facilitate memory, both short term working memory and long term memory. They reduce working memory load by providing external tokens for the elements that must otherwise be kept in mind, freeing working memory to perform mental calculations on the elements rather than both keeping elements in mind and operating on them. A second memory function of external representations is to remind the user of conceptual knowledge necessary for problem solving and of other similar situations that may promote creativity (Goldschmidt 1994). Because diagrams are richer in information than descriptions, they may call to mind a wider range of associations. Moreover, as they are visual and spatial, they are especially appropriate for stimulating visual and spatial associations.

Next, external representations may promote both visuospatial and metaphoric calculation, inference, and insight (e.g., Cox and Brna 1995; Larkin and Simon 1987; Suwa and Tversky 1996; Tversky 1995a, 1995b). For example, inferences, either literal or metaphoric, about size, distance, and direction are easily made from diagrams. Calculations requiring counting or sorting or ordering are easily made by rearranging external spaces (Kirsh 1995). Insights, especially those based on proximity, grouping, and common fate, may be facilitated by inspection of diagrams. Externalization of visual ideas allows them to be inspected, which promotes reorganization, reconceptualization, and reformulation of the same visual display (cf. Reisberg 1987).

Finally, externalizing a set of ideas forces some organization, specificity, and coherence to a set of concepts (Stenning and Oberlander 1995), which, in turn, by inspection, may lead to new discoveries (cf. Goel 1995; Goldschmidt 1991; Schon and Wiggins 1992). Thus, constructing externalizations of a set of concepts serve a function similar to modeling them.

There are a number of advantages to studying the use of external representations in real-world domains where the external representations are produced by problem-solvers and inherent in the problem-solving. The domain we have chosen is that of architectural design. There is some similarity even across cultures in the ways that architects use sketches in designing. Their early sketches, those that are useful in solving the most elemental and essential problems, differ greatly from the architectural plans and models presented to the public (Fraser and Henmi 1994; Laseau 1989; Landay and Myers 1995; Robbins 1994). First, they are sketchy. That is, they are not at all specific. Rather, they tend to use blobs with indeterminate shape to indicate possible spatial arrangements. Next, they are two-dimensional, typically beginning with a plan or overview, a horizontal view. Only after determining the spatial arrangement do architects turn to the vertical plane. As Arnheim (1977) noted, the horizontal plane of architectural drawings defines the plane of function; it shows how people will interact with the environment. The vertical plane is the plane of appearance; it shows how the environment will look to observers.

We have been studying the early stages of the design process by presenting a problem, the design of an art museum, to practicing architects and to architectural students. After working on the design, participants viewed videos of their design sessions and reported what they were thinking as they drew. We have been analyzing those protocols (Suwa and Tversky, in press), and we will report further analyses here. Design sketches are a particularly interesting domain to study as they serve a dual purpose to the designer: they are used to express and demonstrate design ideas and they serve as a graphic display to be inspected to critique, to refine, and to generate further ideas (Goldschmidt 1994).

Review of the Previous Findings on Design Processes

Our previous research had two main results. The first was to classify the types of information that participants perceive and report thinking about as they sketched (Suwa and Tversky 1996; in press). The information fell into three major categories; emergent properties, spatial relations and functional thoughts, each with subcategories to be discussed. Importantly, emergent properties and spatial relations are visual in nature, whereas functional thoughts are inherently non-visual. Designers, especially expert designers, read them off from the visual display.

The second result was to identify the basic units and structure of the design process. The design process proceeds in cycles. First, designers turn their attention to a new design topic from which they start to explore conceptually related topics. When that topic has been exhausted, designers turn their attention to a new topic. We call each fragment of design thought, which is the smallest unit of design processes, a "segment". A segment, whether consisting of one sentence or many, is defined as one coherent statement about a single item/space/topic. We call a set of contiguously occurring segments that are conceptually related to each other a "dependency chunk". See (Suwa and Tversky in press) for the precise definition of "dependency chunk". The basic idea is that if a segment "A" is not related to any segments in the conceptually related sequence that immediately precedes the segment A, then the set of previous segments are grouped into a dependency chunk, and the segment "A" is treated as a focus-shift.

The entire design process consists of many dependency chunks (see Fig.1). Some chunks consist of relatively many segments and others a few. In extreme cases, chunks consist of only one segment. We call it an "isolated" segment. In such cases, a designer shifted attention to a new topic, but failed to explore any related thoughts, and then shifted to another.

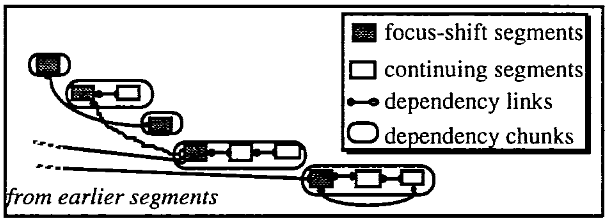

Fig. 1: A schematic diagram of segments, conceptual dependency and dependency chunks

Segments are classified into two types, as shown in Fig.1. One is the first segment in each dependency chunk. It represents a topic to which the designer's attention has been newly shifted. We call it a "focus-shift" segment. The remaining segments that follow a focus-shift segment are called "continuing" segments.

We found evidence that skilled designers had more and longer dependency chunks than novices (Suwa and Tversky 1996; in press). Once experts shift their focus to a new topic, they are more capable of exploring related thoughts. Forming longer chunks leads to deeper and more substantial exploration, and thus contributes to the success of a design process.

The Goal of This Paper

One mark of expertise in architectural drawings as well as other skilled domains is larger chunks of knowledge (Chase and Simon 1973). So, why and how are expert architects able to explore related thoughts more successfully? What are the driving forces that allow them to form longer dependency chunks? We address this question, reducing it to two precise questions. First, what kinds of focus-shifts are likely to prolong subsequent related thoughts? Second, what types of within-chunk thoughts are likely to prolong chunks of related thoughts? To address these questions, we compared the types of information that occurred in longer and shorter chunks.

Experiment

The Architectural Design Task

The experiment consisted of two tasks, a design task and a report task. Five practicing architects and six architectural students 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 told that the curator wants this to be a museum of "light, air and water". They were supposed to use freehand sketches as a tool for designing. Their sketching activity was videotaped.

Following the design task was the report task. While watching their own videotapes, participants were asked to remember and report what they were thinking as they drew each portion of each sketch. Participants were not interrupted with questions during the report. 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 were visible. The content of their verbal report is used for our analysis. Their pointing gestures helped clarify what they were reporting on.

Information Subclasses

The contents of participants' verbal protocols were encoded into subclasses of major categories. The determination of the major categories, i.e. emergent properties, spatial relations and functional thoughts, and their subclasses was based on empirical and theoretical considerations (see Suwa and Tversky, in press).

Emergent properties denote depicted elements and their visual features. The subclasses are spaces in a sketch, physical entities, structural components, shapes, sizes, and materials/textures. Spatial relations denote spatial arrangements among two or more depicted elements. The subclasses are horizontal spatial relations, vertical spatial relations and horizontal global relations. The first two are local in contrast to the third; they are relationships among locally existing elements. Vertical relations primarily refer to structural components that are constructed on top of others. Global relations include locational relationships between the entire site and specific spaces on the site, directions depicted elements face, and rough spatial organization of elements in the site.

The subclasses of functional thoughts are practical roles, abstract features, reactions of people, circulation of people and cars, view issues, light issues. Practical roles denote the roles that designed elements functionally play in a museum. Abstract features denote sensations and emotions that the designer himself feels from visual aspects of sketches. Reactions denote the influence and impact that visitors to the museum would have from the design. The last three subclasses are typical considerations in architectural designs.

Encoding of Verbal Protocols

For each participant, we divided the entire protocol into segments. Then, by analyzing conceptual dependency among segments, we identified the dependency chunks and thereby the distinction between focus-shift and continuing segments. Further, for each segment, we encoded its semantic content into information subclasses. Typically, the protocol for a participant consisted of a few hundred segments. The number of encoded subclasses varied from a few hundred to a thousand, depending on the participant.

RESULTS

Length of Dependency Chunks: Architects vs. Students

We first wanted to reconfirm the difference in the length of chunks between skillful designers and novices because we added a number of practicing architects' data to our previous corpus. First, we calculated the average number of segments in a chunk (ANS) for each participant, and compared it between architects and students. The ANS averaged over the five architects was 2.5 with a standard deviation of 0.48, whereas the ANS averaged over the six students was 1.9 with a standard deviation of 0.18. A statistically significant difference is recognized, $t(9)=2.46$ ($p<0.025$).

Then, for more precise confirmation, we examined to what extent longer streams of related thoughts are dominant in participants' design process: we calculated the ratio of the number of segments belonging to "long" chunks[1] to the total number of segments in the protocol for each participant. The advantage of using this ratio for more precise analysis over the ANS value is that unlike the ANS value the ratio is not affected by the configuration within "shorter" chunks, that is, the distribution of the number of "isolated" segments and the number of chunks whose length is 2. Table 1 shows that the average ratio of the five architects is statistically greater than that of the six students, $t(9)=2.16$ ($p<0.05$). Thus, one salient characteristic distinguishing expert from novice designers is longer streams of segments that are conceptually related.

At the same time, we found that the students happen to divide into two groups by chunk length, as shown in Table

[1] We defined "long" chunks as those whose length is equal to or greater than 3 segments. This is justified by the finding that the ANS value averaged over the architects, who produced longer chunks than students, was 2.5.

1, t(4)=2.56 ($p<0.05$). The three students with higher ratios actually fit within the range of 1σ around the average of architects. So, we added the three students with significantly longer chunks to the sample of five architects to examine characteristics of long chunks. The remainder of the analyses are on these eight "experts".

Table 1: The ratio of the number of segments belonging to long chunks to the total number of segments

Architects		Students			
average (%)	std	average (%)	std		
62.8	11.5	48.9	8.4		
		Students 1-3		Students 4-6	
		average (%)	std	average (%)	std
		55.0	5.3	42.8	6.3

Information Categories: Focus-shift vs. Continuing Segments

Shifting attention to a new topic and exploring thoughts related to a current topic are different mental activities. We examined the difference in terms of the types of information that frequently occur in focus-shift and continuing segments. For each participant, we counted the number of information categories per ten segments, for both kinds of segments. Figure 2 shows the average frequency over the eight participants for both segments for each of the three major categories. Emergent properties are more frequent in focus-shift segments than in continuing segments. Spatial relations are more frequent in continuing segments.

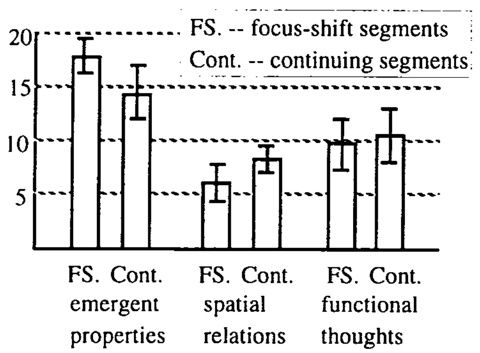

Fig. 2: Average number of pieces of information belonging to the category per ten segments, for each major category for both kinds of segments.

Then, we decided to analyze these phenomena in more detail for each information subclass of each major category within subjects. The reasons are as follows. First, the type(s) of information subclass that each participant frequently thought of in focus-shift or continuing segments may differ from each other, and therefore investigations across subjects may suppress individual differences. Second, the number of subjects is small, so it is difficult to reach statistical significance for the entire group of subjects. However, the number of information subclasses per subject is large, so reaching statistical significance within subjects is feasible. Most of our analyses will be based on the numbers of participants for whom a particular pattern of data is significant.

We examined, for each participant for each information subclass of each major category, whether or not the information subclass occurs statistically more or less frequently in focus-shift segments than in continuing segments. Table 2 shows, for each major category, the number of participants for whom at least one subclass of the major category was more frequent in either type of segment. For most participants, at least one subclass of emergent properties was more frequent in focus-shift segments, and at least one subclass of spatial relations in continuing segments.

This result suggests an overall tendency that emergent properties were more characteristic of focus-shift segments, and that spatial relations were more characteristic of continuing segments.

Table 2: The number of participants, for each major category, for whom at least one subclass of the category was more frequent in either type of segment

	emergent properties	spatial relations	functional thoughts
focus-shift >>continuing	7	2	2
continuing >> focus-shift	1	6	3

Information Categories in Long Chunks: Focus-shift vs. Continuing Segments

Following this, we conducted the same analysis for long chunks only. Differences from the overall tendency may suggest the necessary conditions for long chunks. Figure 3 shows, for each major category for both kinds of segments, the average number of pieces of information belonging to the category per ten segments.

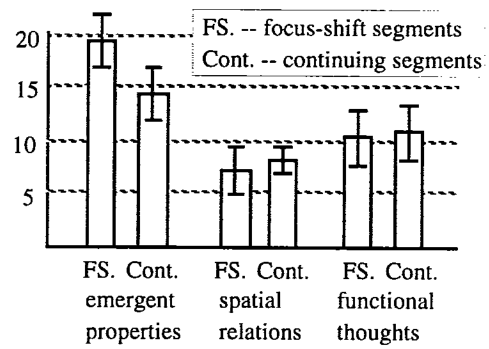

Fig. 3: Average number of pieces of information belonging to the category per ten segments, for each major category for both kinds of segments in long chunks.

For emergent properties, the same tendency as the overall one is observed for long chunks as well: emergent properties were more frequent in focus-shift segments than in continuing segments. For spatial relations, however, the tendency is less salient for long chunks: spatial relations were as frequent in continuing segments as in focus-shift segments.

Then, we examined, for each participant for each information subclass of each major category, whether or not the information subclass occurs statistically more or less frequently in the focus-shift segments of long chunks than in the continuing segments of long chunks. Table 3 is similar to Table 2, showing the number of participants, for each major category, for whom at least one subclass of the category was more frequent in either type of segment. For most participants, at least one subclass of emergent properties was important in the focus-shift segments of long chunks as well. Comparing with Table 3, however, fewer participants (2 instead of 6) exhibited the tendency that at least one subclass of spatial relations was more frequent in the continuing segments of long chunks than in the focus-shift segments of long chunks.

Table 3: The number of participants, for each major category, for whom at least one subclass of the category was more frequent in either type of segment of long chunks

	emergent properties	spatial relations	functional thoughts
focus-shift >>continuing	6	2	3
continuing >> focus-shift	1	2	1

The results may be summarized as follows. The overall tendency that spatial relations are more frequent in continuing segments than in focus-shift segments derives not from long chunks but from shorter chunks. Further, both types of segment in long chunks possess similar characteristics in terms of the frequency of the subclasses of spatial relations.

Information Categories in Focus-shift Segments: Long Chunks vs. Shorter Chunks

These results motivated us to compare long chunks with shorter chunks in terms of the frequency of information subclasses. One comparison is between the focus-shift segments of long chunks and those of shorter chunks. Another is between the continuing segments of long chunks and those of shorter chunks. As far as the latter comparison is concerned, we found no significant differences. This is consistent with the fact that, for all the major categories, the density of pieces of information belonging to each category in the continuing segments of long chunks (shown in Fig.3) is almost the same as those in the continuing segments of the entire protocol (shown in Fig.2). Here, the comparison between the focus-shift segments of long chunks and those of shorter chunks is reported.

Table 4 shows, for each major category, the number of participants for whom at least one subclass of the category was significantly more frequent in the focus-shift segments of long chunks or in those of shorter chunks. First, the number of participants for whom at least one subclass of emergent properties was more frequent in the focus-shift segments of long chunks is five, whereas the corresponding number for those of shorter chunks is three. This means that, for some participants, thinking of certain subclasses of emergent properties in focus-shift segments may prolong the subsequent related thoughts, but may rather shorten them for other participants. In contrast, for a greater number of participants, thinking of subclasses of spatial relations is more associated with long chunks than with shorter ones. For functional thoughts, the tendency is mixed; thinking of subclasses of functional thoughts may or may not be more associated with long chunks than with shorter chunks. To sum, it seems that thinking about subclasses of spatial relations in focus-shift segments is likely to lengthen the subsequent chunks.

Table 4: The number of participants, for each major category, for whom at least one subclass of the category was more frequent in the focus-shift segments of long chunks or in those of shorter chunks

	emergent properties	spatial relations	functional thoughts
long >> shorter	5	5	5
shorter >> long	3	1	2

Table 5 shows, for each participant, the subclasses that he or she more frequently thought of in the focus-shift segments of long chunks than in those of shorter chunks. Importantly, the subclasses that each participant relied on as a driving force for successive exploration differed from each other, yet each participant relied on at least one subclass of spatial relations or functional thoughts. Further, more than one participant relied on horizontal local spatial relations, abstract features, or practical roles. This suggests the significance of these subclasses in focus-shift segments as a driving force of the subsequent exploration, but significant subclasses may not be limited to these because of the small number of participants.

Table 5: The information subclasses, for each participant, that were statistically more frequent in the focus-shift segments of long chunks than in those of shorter chunks

participants	subclasses of emergent properties	subclasses of spatial relations	subclasses of functional thoughts
architect 1		vertical	
architect 2	structure		practical roles, lights
architect 3		global	abstract features
architect 4			practical roles, circulation
architect 5	structure	horizontal	
student 1	spaces	horizontal	
student 2	structure		views
student 3	shape	horizontal	abstract features

Discussion

Expert Designers Have Longer Chunks

One salient difference between expert and novice designers is that experts' protocols have longer sequences of related ideas. This suggests that designers are better able to use sketches to develop more complex design thoughts. One way to promote expertise, then, would be to teach novices to use sketches the way experts do. In order to do that, we need to know what type of thoughts dominate in focus-shift and continuing segments, especially for longer chunks.

Emergent Properties in Focus-shift Segments

With a sample of 5 practicing architects and 3 architectural students with especially long chunks, it is difficult to make statistical comparisons across subjects. Instead, we examined statistically significant patterns within subjects, and found some similarities suggestive of generalities across subjects. First, it seems that thinking about emergent properties was commonly associated with focus-shift more than continuing segments. This tendency was salient also when we observed only long chunks.

Spatial Relations in Focus-shift Segments and Continuing Segments

Second, thinking about spatial relations was commonly associated with continuing more than focus-shift segments, when we observe the overall tendency throughout the entire protocol. This tendency, however, drives from shorter chunks. Actually, in long chunks, spatial relations were not more associated with either type of segment. Investigating the comparison between the focus-shift segments of long chunks and those of shorter chunks, we found a tendency that spatial relations were more associated with the focus-shift segments of long chunks than with those of shorter chunks. Put differently, thinking of spatial relations in focus-shift segments may prolong the subsequent related thoughts.

Locations and Relations in External Representations.

How should these findings be interpreted? Sequences of related thoughts may be longer either because the information in the focus-shift segment is especially successful in stimulating related thoughts or because the primary information used in the continuing segments is useful for continuing related thoughts, or both.

First, thinking about emergent properties seemed to stimulate shifting focus to a new topic. Sketches facilitate this type of action. Emergent properties are visible in or suggested by sketched elements. Simply because the tokens for designed elements are externally represented and thus visible, they become the target of focus shifts. And simply because those elements are organized in locations in a sketch in a specific way, the discovery of implicit empty spaces is facilitated.

Second, thinking about spatial relations, especially horizontal local spatial relations, both in focus-shift segments and during the very exploration of related thoughts was found to be important. Generally speaking, there are three possible cases in which a participant thinks of spatial relations in focus-shift segments. First, he or she revisits a spatial relation that was considered before. Second, he or she tries to create a new element in an empty space, regarding the spatial relation between the element and other existing elements. Third, he or she newly discovers an implicit, thus unintended, spatial relation between more than two existing elements. Sketches facilitate these types of actions as well. A specific organization of elements in a sketch brings the participant's attention to previously attended relations, and even facilitates the discovery of empty spaces and new relations.

Function in External Representations

Whereas using external representations to facilitate thinking about entities or elements and their spatial array is straightforward, thinking about functional aspects of the situation from the external representation requires associations and inferences from the visuospatial display to things that are not purely visual or spatial. In the present analysis, functional thoughts are not more associated with any specific type of segment. However, our previous analyses of the protocols (Suwa and Tversky in press) showed that experts are more adept at perceiving functional thoughts from external representations than novices. This result is suggestive of an important role of external representations. Visual aspects of external representations facilitate associations, reminding and inferences that are necessary for calling to mind non-visual aspects of design thoughts.

Conclusion

We opened by discussing some of the benefits of external representations in thinking and problem solving. As we have shown in our detailed analyses of designers' retrospective reports of their drawing activity in design, sketches serve most of these roles for architects in the design process. Sketches facilitate memory by externalizing the basic design elements, freeing the designer to think about the emergent properties of the elements, the spatial arrangements among them, and the functional implications of the elements and their spatial arrangement. Sketches promote calculations, inferences, and insights by serving as a spatial display on which those mental operations can be performed, and by promoting mental operations based on spatial factors such as proximity, grouping, distance, direction, common fate, and continuity. Finally, sketches facilitate design by inducing designers to be explicit and specific to a certain degree, and thereby to benefit from unintended discoveries.

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