UNEXPECTED DISCOVERIES: HOW DESIGNERS DISCOVER HIDDEN FEATURES IN SKETCHES

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Abstract. Discovering hidden features in a representation without being fixated to a single perspective of viewing it is one of the crucial acts in creative activities. The process of designing through conceptual sketches is no exception; designers should be able to discover in an unexpected way visual/spatial features of sketched elements which were not intended when the elements were being sketched. How are designers able to make unexpected discoveries of this sort? What become the conditions in which unexpected discoveries are likely to happen? We have hypothesised that there are two driving-forces. First, when a designer simultaneously pays attention to a set of previously-sketched elements which have never been attended to together, he or she is likely to make unexpected discoveries in those elements. Second, when a designer has invented a design requirement during the process, the new design concept will enable the designer to view sketches from a new perspective and encourage unexpected discoveries. We examined the cognitive processes of a practising architect, and found that most of his unexpected discoveries were accounted for by these two driving-forces. This has implications for design education and design support.

1. Introduction

Empirically it has been found, and as many scholars have argued (Robbins, 1994; Schon, 1983; Banerji and Elmitt, 1994; Goel, 1995), that drawing freehand sketches during conceptual design plays a crucial role in the birth of creative ideas. Design sketches serve as a medium through which a designer makes visual/spatial reasoning; a designer externalises newly formed but still vague ideas in the form of less rigid and ambiguous depictions on paper. By inspecting those externalised ideas, the designer finds useful clues to refine them, which motivates him or her to draw again. In Schon's terminology, the designer is having a "reflective conversation with his or her idea" (1983). It is due to cyclic behaviors of this sort that design ideas will develop from their infancy to sophistication in the end.

Why and how, then, are designers able to find those useful clues in inspecting their own sketches? What kind of visual/spatial reasoning do designer make using sketches? Goldschmidt (1994) pointed out that perceiving new combinations and relationships among sketched elements which the designer did not anticipate when they were being depicted could provide useful clues. For example, a depiction necessarily takes a certain shape and occupies an area of a certain size on paper, even though these visual features may not be intended by the sketcher. This occurs due to a general aspect of external representations; representing something forces some organization and specificity in terms of visual/spatial features (Stenning and Oberlander, 1995). These unintended visual/spatial features may be discovered in an unexpected way by later inspection, and their discovery could provide useful clues for crucial design ideas.

Our recent study (Suwa, Gero, and Purcell, 1999) has presented supportive evidence for this. We conducted a protocol study of a practising architect and found that the occurrences of unexpected discoveries of this sort have strong correlation with those of inventions of design requirements. The occurrence of an unexpected discovery became the condition for the invention of a design requirement to be likely to happen. The invention of a requirement, in turn, was likely to encourage the subsequent occurrence of an unexpected discovery. What we mean by "invention" is the generation of an important design requirement for the first time in the current design task. For example, our architect, as he worked on the conceptual design of a museum on a given site, came across an important idea which was going to become one of his primary concerns in his design; to locate monumental sculptural pieces near the public road that runs close to the site, in such a way that it will attract the attention of people who drive along the road and thereby convey to them a sense of what this museum is all about. This particular requirement was not given among the initial design requirements, but was invented during the process.

The invention of design requirements is the central act in design activities. Lawson (1990) stressed the importance of analysing through synthesis important aspects of a given design problem. Getzels and Csikszentmihalyi (1976) presented evidence from a longitudinal study of art students which suggests that problem-inventing behaviors are strongly associated with creative outcomes.

According to the recent finding of ours and the discussion on the centrality of "invention" to design, we can conjecture that unexpected discoveries are one key to making a conceptual design process successful. Unexpected discoveries are a form of perceptual interaction with one's own sketches. In other words, that is to detect hidden features of a visual/spatial representation. In order to do this, a designer should be able to defocus from the perspective in which he or she used to look at the representation and replace it with a new perspective. Perkins et. al (1993) counted this as one of the necessary mental tendencies for creative thinking. This corresponds to the act of "making the familiar strange" which the research on synectics (Gordon, 1961) prescribed as the key to a creative outcome.

How, then, is a designer able to discover unintended visual/spatial features in sketches? What are the necessary conditions in which unexpected discoveries are likely to happen? We address this issue in this paper. This examination is expected to provide important implications for design support and design education. For simplicity, we will refer to unexpected discoveries as UXDs in this paper.

Our previous research has shown that UXDs are classified into three types. The first type is to discover among previously-depicted elements a spatial or organisational relation that has never been attended to in the design process before. The second is to attend to for the first time a visual feature of a previously-depicted element, such as its shape, size or texture, that was not intended when the element was being made. The third is to newly perceive an implicit space in-between depictions. We call these three types of UXDs "relation-type", "visual-feature-type", and "implicit-space-type", respectively. Considering that these three are cognitively different forms of perception, it could be that the ways and conditions in which they occur differ from each other. We have made two hypotheses about the necessary conditions in which UXDs are likely to happen. That will be discussed in the next section.

For the purpose of addressing this issue, we have looked into the cognitive processes of a practising architect, using the protocol analysis technique. In the third section, we will briefly describe the protocol data we have used, the scheme of coding the data, and the definition of UXDs in the coding scheme. We will present the results in the fourth section, and discuss them in the fifth section.

2. Hypothesis

2.1. CONCEPTUAL DRIVING-FORCE

Our recent finding mentioned in the introduction, i.e. that the occurrence of the invention of a new design requirement was likely to encourage the subsequent occurrence of UXDs, suggests a necessary condition in which UXDs are likely to happen. Thus, we have come to the following hypothesis;

> the existence of an idea which has never occurred before tends to let a designer defocus from previous ways of perceiving the sketches, and thus encourages UXDs.

Howard-Jones (1998) has presented supportive evidence for this. He did an experiment in which subjects looked at a geometrical shape and generated as many interpretations of the shape as possible. Each subject, once he or she generated an interpretation, was supposed to throw it away to generate another interpretation. In order to do that, the subject should be able to defocus from visual/spatial features which were salient to his or her perception, and thereby to look at the same shape from a different viewpoint. This act exactly corresponds to what we call UXDs. Howard-Jones divided subjects into two groups. In the experimental group, every time he or she generated an interpretation, the subject was presented with a nonsense sentence, and was told to select one word from the sentence and to generate a new interpretation of the shape in a way associated with the concept of the word. In the control group, the subject tried to generate a new interpretation without a presentation of a word. The finding was that the existence of the word contributed much to the increase of the production rate of new interpretations.

Both inventing a design requirement and thinking around the concept of a presented word belong to conceptual processing. We use the terminology, conceptual processing, in the sense that there are multiple levels at which information coming into a human cognitive system is processed, i.e. sensory, perceptual and conceptual processing. Thus, we call the hypothesis mentioned above the "conceptual driving-force" to make UXDs happen.

Our finding suggesting the feasibility of this hypothesis, however, was the result of dealing with the three types of UXDs together. Considering that the conditions in which the three types happen could differ from each other, we need to make a more precise analysis for each type.

2.2 SENSORY DRIVING-FORCE

Design sketches are a kind of diagrammatic representation. Other examples include diagrams, drawings, pictures, icons, graphs, and even doodles. Researchers in cognitive science have discussed the aspect of diagrammatic representations that facilitates people's problem-solving and inference (Chandrasekaran, Glasgow and Narayanan, 1995). One relevant aspect is specificity, as we mentioned in the introduction. Another is that diagrammatic representations do not encode information sequentially; unlike sentential representations, people are able to see a diagrammatic representation in its entirety, even though it consists of many components depicted on paper at different times.

These two aspects enable a simultaneous view of components in a representation, which were produced at different times during the process. This applies to design sketches as well. Therefore, we have made a second hypothesis about the condition in which UXDs are likely to happen;

> if a designer happens to pay attention to sketched elements which he or she has never attended to simultaneously before, then the designer is likely to defocus from the visual/spatial features of those elements that he or she used to attend to, and be able to discover new features of the elements.

Attention to the existence of sketched elements belongs to the sensory level of information processing in human cognition. Thus, we call this the "sensory driving-force" to make UXDs happen.

3. Protocol Analysis

3.1 PROTOCOL DATA

We have looked into the cognitive processes of a practising architect using the technique of protocol analysis. The protocols of his design session were collected as a retrospective report after the session (Suwa and Tversky, 1997). The design session, which lasted for 45 minutes, was to work on the conceptual design of a museum on a given site in the suburb of a large city. The architect was encouraged to draw sketches on tracing paper. His sketching activities were videotaped. In the report session, he described, while watching the videotape, what he had been thinking of for each stroke of his pencil during the design session.

3.2 CODING SCHEME: OVERVIEW

We developed a coding scheme that is suitable for examination of cognitive processes of designers (Suwa, Purcell and Gero, 1998). We will give a brief overview of the scheme.

3.2.1 Segmentation

As many previous protocol analysis methods have done, we divide the entire verbal protocol into small units, that is, segmentation. The method of segmentation we employed is to divide the protocol based on the subject's intention, the contents of their thoughts and/or their actions (e.g. Goldschmidt, 1991; Van Someren et. al, 1994; Suwa & Tversky 1997; Gero & McNeill, 1998).

3.2.2 Different Modes of Cognitive Actions

For each segment, we code different modes of designers' cognitive actions. There are four modes: physical, perceptual, functional and conceptual. The first category, **physical,** refers to actions that have direct relevance to physical depictions on paper. It consists of two classes: drawing-actions and looking-actions.

Drawing actions are divided into two categories. One is to draw a new element, and the other is to trace over, or copy on another sheet, a previously-drawn element. One crucial issue in coding actions of drawing new elements is how we should segment fluid drawing strokes into instances of separate actions. We employ the following principles; we interpret as a single action a chunk of strokes which the designer intended to be of one meaning. In order to do this, we use not only the video information of the designer's sketching activities but also the semantic contents of his or her verbal protocols. According to this principle, strokes with different shapes, such as lines, dots, circles and so on, are often coded as separate actions. And, even if a certain shape was depicted with multiple strokes, we code those strokes as comprising a single action as a whole, as long as the designer intends the shape to refer to a single meaning. For each drawn element whose strokes are coded as a single action, we give an identification to the element. For an action of tracing over or copying, we record the identification of the element traced over or copied.

A looking-action is to pay attention to the existence of a previously drawn element, without any involvement of drawing-actions. We seek justification for looking-actions, by interpreting the contents of the verbal protocol in terms of which elements the designer is talking about. For each instance of looking-action, we record the identification of the element which the designer paid attention to.

The second category, **perceptual**, refers to actions of attending to visual/spatial features of depicted elements. There are four classes of perceptual actions: (1) visual features of elements, such as shapes, sizes, or textures, (2) spatial relations among elements, such as proximity, remoteness, alignment, intersection, connectedness and so on, (3) organisational relations or comparison among elements, such as grouping, uniformity/similarity, contrast/difference, and (4) implicit spaces that exist in-between depicted elements. We collect instances of perceptual actions from verbal protocols, interpreting the semantic contents of the protocol.

The third category, **functional**, refers to actions of associating depicted elements or their visual/spatial features with meanings, functions or abstract concepts. This category, however, is not relevant to the purpose of this paper.

The fourth category, **conceptual**, refers to higher cognitive actions, such as the set-up of goals, preferential or aesthetic evaluations, and the retrieval of knowledge or past similar cases. Out of these, the set-up of goals is relevant to the purpose of this paper; the invention of a design requirement appears in protocols as the act of setting up a goal to bring it into reality. We will describe the coding of goals in Section 3.4.

3.3 THE DEFINITION AND CODING OF UXD

We define UXDs as a particular class of perceptual actions; that is, a first-time perception of new visual/spatial feature(s) of element(s) depicted in a previous segment. Due to this definition, the occurrence of a UXD in a segment necessarily involves the revisit of at least one previously-depicted element. The revisit appears as looking-action(s) or action(s) of tracing over.

Dependent on the kind of perceptual actions, UXDs are categorised into there distinct types; "relation-type", "visual-feature-type", and "implicit-type". If a designer for the first time perceives a relation, spatial or organization, among a set of revisited elements, it is an instance of "relation-type" UXD. For example, suppose that an architect traces over an element and at the same time pays attention to another element near the first element, and notices the proximity between the two for the first time. The attention to this proximity belongs to this type.

If a designer attends to a new visual feature of a revisited element, such as its shape, size, or texture, it is an instance of "visual-feature-type" UXD. For example, suppose that an architect traces over a circular line that was originally a simple indication of the area for an entrance hall of a museum building, and now begins to attend to its circular shape for the first time. This attention to the shape belongs to this type.

If a designer attends to a new implicit space between depictions, it is an instance of "implicit-type" UXD. This is so-called perception of figure-ground reversal, one of the characteristics of human perception. A famous example from psychology is perception of a single vase versus the contours of two human faces facing each other. Arnheim, under a chapter titled "solids and hollows" in his book (1977), has given many examples of this in the context of architectural design.

3.4 THE CODING OF INVENTIONS OF DESIGN REQUIREMENTS

Our previous research (Suwa, Gero, and Purcell, 1999) classified into several types goals which a designer sets up during the design process. Table 1 summarises all the types. There are four major types: goals to introduce a new function (Type 1 goals), goals to give a solution to a problematic conflict in the current design (Type 2 goals), goals to apply previously-introduced functions in the current context (Type 3 goals), and repeated goals from a previous segment (Type 4 goals).

Type 1 goals are, in turn, divided into several subclasses. The first subclass is a goal to create, in a new spot in the sketch, a function listed in the initial requirements given to the architect (Type 1.1). The second is a goal to introduce a new function as prescribed by a piece of knowledge or a past similar case (Type 1.2). The third is a goal extended from a previous goal. One form of extension is to add a more concrete specification to the function which the previous goal dictated. Another form of extension is to generalise the issue dealt with in the previous goal and bring it into a broader context. The fourth is a goal to create a new function in a way that is not supported by initial requirements, knowledge, or previous goals (Type 1.4). When there is no evidence in the verbal protocol as to how the architect conceived of the goal, we code it into this category.

Table 1. Types of goals to invent new functions and issues

Type 1: goals to introduce new functions	
Type 1.1:	based on the given list of initial requirements
Type 1.2:	as prescribed by explicit knowledge or past cases
Type 1.3:	as a extension from a previous goal (subtypes: specifying & broadening)
Type 1.4:	in a way that is not supported by knowledge, given requirements, or a previous goal
Type 2: goals to give a solution to a problematic conflict	
Type 3: goals to apply previously introduced functions or arrangements in the current context	
Type 4: repeated goals from a previous segment	

Which types of goals should be interpreted as instances of "inventions of important design requirements"? The word "invention" has the connotation that goals for invention should be at least new and original. Therefore, Type 1.1, Type 3, and Type 4 goals should not be included. The remaining types of goals are divided into two categories; Type 1.2 versus the others. Type 1.2 goals are set up according to the prescription of what a piece of explicitly articulated knowledge or past cases dictates. On the other hand, the others are set up by being mediated by tacit knowledge. For example, although we are able to identify a previous goal as the source of a Type 1.3 goal, we are unable to identify any explicit knowledge that let the designer conceive of the particular form of extension. He just conceived of that extension. This applies to Type 1.4 and Type 2 as well. The designer just conceived of a particular function, and a particular solution, respectively. According to our previous research (Suwa, Gero and Purcell, 1999), it was the summation of Type 1.3, Type 1.4 and Type 2 that had significant correlations with the occurrence of UXDs; the summation of the four types of goals including Type1.2 did not correlate with UXDs. Therefore, for the purpose of this paper, we interpret the summation of Type 1.3, Type 1.4 and Type 2 goals as goals for inventions of design requirements.

4. Results

4.1 CODING OF UXDS AND GOALS FOR INVENTION

The entire protocol of our architect contained 340 segments. For each segment, we coded instances of unexpected discoveries and goals. The entire protocol contained 606 perceptual actions, out of which 171 were unexpected discoveries. The fact that a significant portion of the perceptual actions, 28%, belonged to UXDs clearly shows its importance in the design process of our architect. Table 2 shows the occurrences of each type of UXDs. 107 UXDs belong to "relation-type", 36 to "visual-feature-type", and 28 to "implicit-space-type".

In addition, we identified and coded 85 goals for inventions of design requirements throughout the entire design process.

Table 2: The occurrences of unexpected discoveries

types of UXDs	number of occurrences	percentage to the total (%)
relation	107	63
visual-feature	36	21
implicit-space	28	16
total	171	

4.2 COMBINATION OF REVISITED ELEMENTS

We will describe how we judge whether the combination of previously-drawn elements which a designer revisits in a segment is for the first time or a repeated one from a segment in the past. First, the acts of revisiting previously-drawn elements in a segment is defined as the summation of (1) looking-actions and (2) actions of tracing over or copying on another paper previous elements. Our coding scheme provides, for each action belonging to these, the identifications of the corresponding elements. This means that we have a set of identifications of the revisited elements for each segment. We denote a set of identifications of the revisited elements in segment *i* as *REi*.

On the other hand, a designer's simultaneous attention to elements in a segment is defined as the summation of all the physical actions in the segment. Whether a designer draws new elements and/or pays attention to previously-drawn elements, we assume that he or she is simultaneously attending to all those elements involved. This means that we have a set of identifications of the attended elements for each segment. We denote a set of identifications of the attended elements in segment *i* as *AEi*.

We judge, for every segment, whether or not the combination of the revisited elements is new, in the following manner. If *REi* is not a null set, and if *REi* is neither the same as *AEj* nor a subset of *AEj* for all *j* such that $j < i$, then *REi* is a new combination of revisited elements. *REi* being a null set means that the designer did not revisit any previously-drawn elements in segment *i*.

Table 3 shows how many segments out of the entire 340 segments belonged to the three classes in terms of the combination of revisited elements. Our architect revisited previously-depicted elements in a new combination (Class A) in 136 segments, i.e. 40% of the entire design process. He revisited previously-depicted elements in exactly the same as, or as a subset of, a previous combination (Class B) in 182 segments, i.e.

54 %. In 22 segments, he did not revisit any previously-depicted elements (Class C).

Table 3: The ways in which a practising architect revisited previously-depicted elements

the combination of the revisited elements in a segment	number of segments	percentage to the total (%)
Class A: new combination	136	40
Class B: the same as, or a subset of, a previous combination	182	54
Class C: No revisited elements	22	6
total	340	

4.3 THE CONDITIONS IN WHICH UNEXPECTED DISCOVERIES OCCUR

The "sensory driving-force" hypothesis dictates that UXDs are likely to happen in a segment if the combination of the revisited elements in that segment is new. The "conceptual driving-force" hypothesis dictates that the existence of a new concept, a goal for inventions of design requirements in this paper, sets a condition in which UXDs are likely to happen.

We examined the former hypothesis as follows. For each type of UXD, we have examined how many UXDs occurred in Class A and Class B segments shown in Table 3. If the "sensory driving-force" hypothesis is not true, the occurrences of UXDs would be distributed to each class of segments in proportion to the ratio of the number of each class to the total. If the hypothesis is true, more instances of UXDs would be distributed partially to Class A segments.

We examined the latter hypothesis as follows. We classify all the segments into the following two classes: (1) Class 1 - segment which has at least one instance of invention of a design requirement or whose immediately previous segment has at least one instance of invention of a design requirement (we call this "next of or together with inventions"), (2) Class 2 - segment which does not have an instance of invention of a design requirement, and also whose immediately previous segment does not have an instance of invention of a design requirement either (we call this "no immediate existence of inventions"). For each type of UXD, we have examined how many UXDs occurred in the two classes of segments. If the "conceptual driving-force" hypothesis is not true, the occurrences of UXDs would be distributed to each class in proportion to the ratio of the number of each class to the total. If the hypothesis is true, more instances of UXDs would be distributed partially to Class 1 segments.

4.3.1 Relation-type UXDs

Table 4 shows the occurrences of relation-type UXDs in each of Class A and Class B segments shown in Table 3. The "sensory driving-force" hypothesis is true to "relation-type" UXDs; statistically, more relation-type UXDs occurred in segments in which the combination of revisited elements was new, than in the other segments. Table 5 shows the number of segments belonging to each class categorised in relation to the occurrences of goals for inventions, and the occurrences of "relation-type" UXDs at each class of segments. Statistically, the occurrences of UXDs were not distributed partially to either class of segments; the "conceptual driving-force" hypothesis does not hold, as far as relation-type UXDs are concerned.

Table 4: The occurrences of "relation-type" UXDs in the two kinds of segments categorised in terms of the combination of revisited elements

		"relation-type" UXDs	
the combination of the revisited elements in a segment	number of segments	number of occurrences	frequency per segment
Class A: a new combination	136	65	0.48
Class B: the same as, or a subset of, a previous combination	182	42	0.23
total	318	107	
statistical test of distribution		$\chi^2(1)=14.1$ ($p<0.005$)	

Table 5: The occurrences of "relation-type" UXDs in the two classes of segments categorised in relation of the occurrences of goals for inventions

		"relation-type" UXDs	
classes of segments	number of segments	number of occurrences	frequency per segment
Class 1: next of or together with inventions	133	45	0.34
Class 2: no immediate existence of inventions	207	62	0.30
total	340	107	
statistical test of distribution		$\chi^2(1)=0.39$ ($p>0.5$)	

4.3.2 Visual-feature-type UXDs

Likewise, we examined the occurrences of visual-feature-type UXDs in Class A and Class B segments, categorised in terms of the combination of revisited elements. 18 UXDs occurred in Class A segments, and 18 in Class B segments. Statistically, the occurrences of UXDs were not distributed partially to either class ($\chi 2(1) = 0.77$, $0.25 < p < 0.5$). We examined the occurrences of this type of UXDs in Class 1 and Class 2 segments, categorised in relation to the occurrences of goals for inventions. 17 UXDs occurred in Class 1 segments, and 19 in Class 2 segments. The occurrences of UXDs were not distributed partially to either class ($\chi 2(1) = 0.99$, $0.25 < p < 0.5$).

However, when we combine both effects, i.e. "a new combination of revisited elements" and "the immediate existence of inventions", a different result was observed. We have categorised the entire 340 segments into the following two classes: (1) Class 3 - segment in which the combination of revisited elements is new, and also which has at least one instance of invention of a design requirement or whose immediately previous segment has at least one instance of invention of a design requirement, (2) Class 4 - the remaining segments. Table 6 shows the occurrences of visual-feature-type UXDs at Class 3 and Class 4 segments. Statistically, more visual-feature-type UXDs occurred in Class 3 segments than in Class 4 segments. Both "sensory" and "conceptual" hypotheses are true; visual-feature type of UXDs are likely to happen only when there are both sensory and conceptual driving-forces.

Table 6: The occurrences of "visual-feature-type" UXDs in the two classes of segments categorised both in terms of the combination of revisited elements and in relation of the occurrences of goals for inventions

classes of segments	number of segments	"visual-feature-type" UXDs	
		number of occurrences	frequency per segment
Class 3: a new combination of revisited elements AND "next of or together with inventions"	52	11	0.21
Class 4: the remaining segments	288	25	0.09
total	340	36	
statistical test of distribution		$\chi^2(1)=6.47$ ($p<0.025$)	

4.3.3 Implicit-space-type UXDs

Statistically, the occurrences of implicit-space-type UXDs were not distributed partially to either class of segment in the three different analyses we have shown. 10 implicit-space-type UXDs occurred in Class A segments, while 18 in Class B ($\chi 2(1) = 0.57$, $0.25 < p < 0.5$). 12 implicit-space-type UXDs occurred in Class 1 segments, while 16 in Class 2 ($\chi 2(1) = 0.16$, $0.5 < p < 0.75$). 2 implicit-space-type UXDs occurred in Class 3 segments, while 26 in Class 4 ($\chi 2(1) = 1.44$, $0.1 < p < 0.25$). Neither "sensory driving-force" hypothesis nor "conceptual driving-force" hypothesis hold for implicit-space-type UXDs.

5. Discussions and Implications

5.1 THE DRIVING-FORCES TO MAKE UNEXPECTED DISCOVERIES HAPPEN

Two factors, the immediate existence of the invention of a design requirement and attention to previously-depicted elements in a new combination, accounted for the occurrences of "relation-type" and "visual-feature-type" UXDs. The significance of both factors as the driving-forces to make unexpected discoveries happen is reinforced by the fact that the two types of UXDs cover 84% of the total number of UXDs.

This result has verified the anecdotal view that one of facilitatory aspects of diagrammatic representations such as sketches is to allow for a view of the entire information. Our architect, in 40% of the entire design process as shown in Table 3, simultaneously attended to elements that he had depicted at different times during the process and therefore had never attended to together. And when he did so, he was more likely to make relation-type UXDs. As long as he paid attention to previously-depicted elements in the same as, or as a subset of, a previous combination, his attention was fixated to the relations which he had seen among those elements. Thus, he was less likely to detect new relations which may be hidden in the previous combination.

Attention to previously-depicted elements in a new combination did not suffice to encourage the occurrences of visual-feature-type UXDs; both "conceptual" and "sensory" driving-forces were required. The involvement of the conceptual driving-force is corroborated by the prevailing view that people's perception is affected by what they know and/or what they are conceiving of (e.g. Clancey, 1997). The result of the present research has provided an illustrative example of this.

Neither conceptual nor sensory factors accounted for the occurrences of "implicit-space-type" of UXDs. Generally speaking, this type of UXD corresponds to perception of figure-ground reversal. The ways or conditions in which they occur are still unclear and yet to be explained by future research.

5.2 IMPLICATION FOR DESIGN EDUCATION

An ideal way to cognitively interact with one's own design sketches is to discover as many hidden visual/spatial features in the sketches as possible. For, as discussed in the introduction, doing this will provide a designer with clues to invent important design requirements, which may be related to the birth of creative outcomes. The results of this paper have laid the foundation for possible advice on how to discover hidden features in sketches. First, a designer should be well aware that there are at least three distinct types of hidden features; relations, visual-features and implicit-spaces. Second, a designer should try to simultaneously pay attention to sketched elements which he or she has never attended to together before, and to discover new relations which may potentially be hidden among those elements. Third, especially when he or she has generated an inventive design requirement, a designer should not only pay attention to previously-sketched elements in a new combination but also try to reorganise his or her perception to sketched elements in terms of the new-born requirement. These could be used as plausible ways to educate novice designers about designing through sketching.

These advices, however, are necessary requirements for a successful outcome of a conceptual design process, but may not be sufficient conditions. As we mentioned in the introduction, our practising architect successfully took advantage of unexpected discoveries as a driving-force to access his tacit knowledge and thereby invent design requirements (Suwa, Gero, and Purcell, 1999). However, a question still remains unanswered. Are unexpected discoveries really a gateway from which even a novice designer is straightforwardly able to access his or her tacit knowledge and thereby invent design requirements? Or, does only making unexpected discoveries not suffice to provide a designer with a straightforward path to the invention of design requirements? Does a designer still require skills or expertise to take advantage of the unexpected discoveries that he or she made? To answer this question, we will need further studies that compare practising architects and students in terms of the correlations between unexpected discoveries and inventions of design requirements.

5.3 IMPLICATION FOR DESIGN SUPPORT

Improvement of the quality of design processes and products can be facilitated by appropriate and useful support by computational tools.

Many scholars have stressed the importance of design support, especially in the early conceptual design processes, and have developed pen-based electronic sketching tools (e.g. Gross, 1996; Kramer, 1994). Gross's Cocktail Napkin (1996) monitors the shapes of the elements sketched on the pad, and thereby allows the user to search for past cases in architectural archives and databases which contain a similar shape. Kramer (1994) proposed a mechanism to enable its user to integrate and structure sketched elements flexibly, and thereby to dynamically change associations from sketched elements as the sketching process goes on.

The present research has implied the significance of a different type of support; that is, enhancement of perceptual interaction with sketched elements. Its notion was originally proposed in (Suwa, and Tversky, 1997; Suwa and Gross, manuscript; Suwa, Gero, and Purcell, 1997). If an electronic sketching pad has the ability to monitor and store the information of what has been sketched and to highlight a particular set of sketched elements using superimposed colors, it might be able to arouse a sketcher's attention to potential spatial relations between those highlighted elements. For example, if it is conjectured that it would be important for a designer to simultaneously attend to elements which happen to be adjacent to each other, then highlighting a set of adjacently-located elements might work as a useful visual stimulus to the perception of the designer.

There has been lack of insight, however, about which particular set of elements could be the target of simultaneous highlighting. The present research has provided part of the answer to this question. The verified hypothesis about the "sensory driving-force" for UXDs suggests that it may be fruitful to arouse a designer's attention to a set of sketched elements which were not depicted closely together chronologically during the design process. Suppose that an electronic sketching tool is provided with a certain algorithm to segment what is being sketched on the pad into separate elements, and is able to record the information about when each element was sketched. Then, it would be possible that the tool generates combinations of sketched elements which were not sketched closely together chronologically, and selects one of these combinations for visually highlighting. Among many possible combinations, how does the sketching tool select one? More insights are needed from future research to trim down the number of candidate combinations. If we obtain insights on this, visual highlighting of a selected set of elements could be useful to arouse a designer's attention to potentially hidden visual/spatial features of those elements.

Conclusion

Discovering in an unexpected way visual/spatial features of sketched elements which were not intended when the elements were being sketched is crucial in a conceptual design process; it may be related to the birth of creative design ideas. The purpose of this paper was to examine the conditions in which unexpected discoveries (UXDs) are likely to happen.

We have hypothesised that two factors may become the driving-forces to make UXDs happen. First, when a designer simultaneously pays attention to a set of previously-sketched elements which have never been attended to together, he or she is likely to make UXDs. This is a "sensory" driving-force. Second, when a designer has invented a design requirement during the process, the existence of the new design concept will enable a view of sketches from a new perspective and encourage UXDs. This is a "conceptual" driving-force.

We have examined the cognitive processes of a practising architect and obtained the following findings. UXDs are classified into three different types, i.e. relation-type, visual-feature-type, and implicit-space-type. The conditions for these three to be likely to happen differ from each other. The occurrences of relation-type UXDs are encouraged when there is the "sensory" driving-force. The occurrences of visual-feature-type UXDs are encouraged when there are both "sensory" and "conceptual" driving-forces. The occurrences of implicit-space-type UXDs were not accounted for by either of the two driving-forces. Our hypothesis has been verified by the fact that the first two types of UXDs cover 84% of the total number of UXDs.

These results have a pedagogical implication; it suggests possible advice to novice designers about how to discover hidden visual/spatial features in their own sketches. Further, these have implications for the feasibility of a new type of design support; enhancement of perceptual interaction with sketched elements.

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