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EXPLORATION THROUGH DRAWINGS IN THE CONCEPTUAL STAGE OF PRODUCT DESIGN

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Abstract. This paper argues that sequences of exploratory drawings - constructed by designer's movements and decisions - trace systematic and logical paths from ideas to designs. This argument has three parts. First, sequences of exploratory sketches produced by product designers, against the same task specification, are analyzed in terms of the cognitive categories of reinterpretation, emergence and abstraction. Second, a computational model is outlined for the process of exploration through drawing and third the model is applied to elucidate the logic in the sequences of exploratory sketches examined earlier.

1. Introduction

Designers rely on visual representations to generate and explore design ideas. It is assumed here that there is a reciprocal relationship between designers' thinking and their representations. Representations may be a consequence of thinking but also thinking may be stimulated by perception of representations. These connections suggest that exploratory representations might trace logical paths from an original idea to a final design. One characteristic that differentiates expert designers from novices is the skill of constructing a logical path that brings preliminary ideas to final designs rather than the ability to come up with isolated ideas. This paper argues that this path –constructed by designers' movements through sequences of drawings and decisions– is systematic and logical.

Visual representations and particularly freehand sketches are not just used as a way of communicating or storing ideas, but they also serve as a tool to assist thinking (Goel 1995). Sketches in conceptual stages support divergent and convergent thinking. While in divergent thinking designers generate alternative and isolated concepts, in convergent thinking these are synthesised and evaluated (Liu, Bligh et al. 2003). Cross (1994) points out that, in general, the design process is convergent, but also contains deliberate divergent thinking for the purpose of opening the search for new concepts. This paper concentrates on sketches generated during convergent thinking.

Designers use many different types of sketches corresponding to different design stages and cognitive processes (Lawson 2004). For example, sketches produced in early stages tend to be more ambiguous and less complex than later stages of the design process. Goel (1995) argues that, on the one hand, designers need ambiguous and vague sketches in order to keep options open. But on the other hand, designers also guide the design to a conclusion setting boundaries, selecting particular objects and relations for attention, and imposing a coherence that guides subsequent moves (Schon 1988).

Designing includes reflective ‘conversation’ with sketches and other representations, generated (Schon and Wiggins 1992). Designers proceed by seeing, moving and seeing again. Goldschmidt (1994) notes that designers transform designs in a cyclic manner. Each sketch is interpreted by designers, transforming the previous sketch by adding, deleting, modifying or replacing certain parts. This reflective 'conversation' leads to the generation of related sketches where each design emerges from previous designs.

The path leading to the final design cannot be foreseen, and each transitional design generated is a potential turning point where the path can change its course. How designers perceive shapes in drawings offers a point of departure in understanding the exploration process in design. In conceptual stages of the design process, visual representations tend to be ambiguous and vague which promotes changes of interpretation. How design features are perceptually grouped and how unintended features emerge during the design process appear to be critical in understanding the conceptual stage of design. Penetrating into designers' reasoning is not straightforward, perhaps unachievable, but examination of how they see, change and move through external representations may give insight into design thinking.

This paper has three parts. First, sequences of exploratory sketches produced by product designers, against the same task specification, are analysed in terms of the cognitive categories of reinterpretation, emergence and abstraction. Second, a computational model is outlined for the process of exploration through drawing and third the model is applied to elucidate the logic in the sequences of exploratory sketches examined earlier.

2. Visual perception in design exploration

In early conceptual stages designers often use both imagery and visual perception simultaneously to explore new design alternatives (Goldschmidt 1994). While imagery allows exploring designs through the mind’s eye, visual perception requires the support of visual stimulus such as sketches.

Although both mechanisms proceed similarly (Kosslyn 1990), the design consequences produced from imagery and visual perception may be different. For example, Fish and Scrivener (1990) point out that the ambiguity of sketches amplifies imagery mechanisms, and that sketches serve to originate new interpretations by the visual and cognitive systems. On the other hand, Kosslyn points out that one of the purposes of imagery is anticipating what will happen if a physical object is modified in a particular way. See Purcell and Gero (1998) for a review of protocol studies of the roles of imagery and sketching in design. This paper concentrates on the exploratory drawings themselves, how they are perceived, modified and reinterpreted.during the design process.

Design sketches produced in exploratory stages are not always external representations of internal mental images. Rather they may be used as a way of thinking rather like talking out loud as a way of thinking (Smithers 2001). Making and examining sketches may motivate further sketching. The perception of sketches in design exploration assists designers in (i) inspecting compositions of designs as well as examining subtle features and (ii) discovering new design interpretations (Suwa and Tversky 2003). The review of these two processes offers a starting point for this paper.

Psychology and cognate disciplines aimed to detect and understand general rules of perception. Gestalt psychologists presented theories on perceptual preferences, mainly on visual grouping. In particular they sought to explain visual preferences, and how shapes are organised into meaningful compositions. Arnheim (1974), for example, argues that many people see Fig. 1a as unbalanced. Its composition looks accidental, transitory, and somewhat illogical. According to Arnheim 'the circle looks as though it had been at the centre and wished to return, or as though it wants to move away even farther'. He adds that the circle is not only influenced by the boundaries of the square, but also by imaginary cross and diagonals that divide the square in symmetrical parts, which he refers to as the *structural skeleton.*

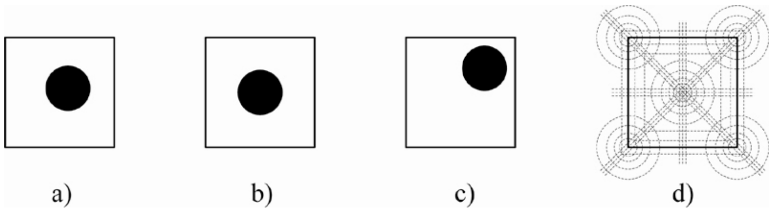

Figure 1. (a) Unbalanced composition, (b) and (c) balanced compositions, (d) structural skeleton of the square by Arnheim.

The composition shown in Fig. 1b when the circle and the square share the same centre is more stable and settled The composition in Fig. 1c may be perceived as more balanced than Fig 1a. In general, a position of the circle that coincides with a feature of the structural skeleton will appear balanced.

Typically, drawings are composed of shape elements arranged in space relative to each other and relative to a reference frame (Tversky 2001). The reference frame is similar to the idea of structure. Interpreting and understanding a drawing involves grouping certain elements in a particular way and assigning a structure. Designers are sensible to this requirement when they arrange the elements in a design, and while exploring new designs seek out the most suitable layouts of perceived elements. For example, Akin (2001) notes that architects continue to search for alternative solutions even when they have developed satisfactory designs One argument in favour of the existence of structure is that some shape transformations lead to refinements of the concept design whilst other types of transformations lead to different concept designs (Goel 1995). This suggests that some shape transformations entail structure manipulation. Completely different sketches may be perceived as the representation of the same concept design, even if they do not share a similar outline. Conversely, similar sketches may be interpreted as the representation of different concept designs. Reversing figures, such as the duck-rabbit figure, offer a good example of this phenomenon. Stacey (2005) points out the importance of structure in style judgements. People often regard shared structure as more important than shared features, for example, AA may be seen as more similar to BB than to AC.

A structure can be used to guide the exploration of new designs. The structure is related to the perceptual organization of the elements. That is, the structure reveals a particular interpretation of the design. Similarly, Suwa and Tversky (2003) refer to constructive perception which involves organizing perception in the search for new interpretations. Arnheim (1974) argues that visual perception is dynamic, and therefore recognition of structure of objects necessarily involves active participation of the viewer, as for example,, proposed by Kepes (1944) for abstract paintings.

Discovering hidden features in sketches is one of the crucial acts in conceptual design, and may be related to the production of creative design ideas (Suwa, Gero et al. 1999). Protocol analyses have suggested that expert designers are more adept at perceiving hidden features than novices (Suwa 2005). The reinterpretation of visual shapes in design enables emergence. Gero (1996) examines the role of emergence in creative design.

In the exploration of new design alternatives, designers modify the elements of the design according to the perceived structure. However, the structure may also be modified by seeing different elements. If the structure is viewed at a higher level of abstraction this reduces the complexity of designs and assists in understanding aesthetic properties, such as balance in composition. Designers switch between different levels of abstraction and use abstract models to test design decisions . Hoover et al. (1991) propose that these models provide a framework for making design refinements. They argue that while making a design refinement, the designer explicitly considers only those design object characteristics which are included within the current abstraction. That is, shape refinements are made within the framework of the perceived structure. The levels of detail used in sketches determine the levels of detail of their abstractions. They also point out that during the design process the level of detail decreases and increases.

The reviewed literature suggests that shapes can be perceived in multiple ways. Changes in perception may occur when the elements of a design and their relationships are interpreted differently. Although these differences are not explicitly represented in the drawing, they are perceived visually in the form of structure. Identifying a structure for a shape guides the exploration process. The path this exploration takes will be altered whenever the structure is newly reinterpreted. Perception of emergent features may provoke reinterpretation of the structure. In the present study, we examine drawings produced by designers during design exploration focusing on the mechanisms of reinterpretation, emergence and abstraction in the conceptual stage of design.

3. An empirical study of design exploration

Several studies have observed how professional designers and design students develop specific cognitive strategies.. Goel (1995), for example, observed that, in convergent thinking, two types of strategies occur between successive sketches; lateral transformation and vertical transformations. While lateral transformations are used for widening the problem space by moving from one idea to a slightly different idea, vertical transformations deepen the design by moving from one idea to a more detailed or refined version of the same idea.

One way of examining designers’ reasoning is by observation of their sketches through protocol analysis. However, many of these studies have focused on designers ‘seeing’ rather than designers ‘moving’ thus neglecting the investigation of shape relations among sketches. Here we examine the kinds of moving used in the creative stages of product design.

This study is concerned with visual representations, particularly with what has been termed ‘thinking sketches’ (Ferguson 1992), While design thinking is not the main issue here, sometimes it is necessary to speculate on the designer's thoughts in order to interpret shape transformations in sketches.

3.1. THE EXPERIMENT

There are different methods of investigating the design process and each has its strengths and weaknesses. For example, formal 'think-aloud' protocols, where participants are asked to review and talk through their work, is widely used for seeking insights into designers' creative activities such as sketching. In the presented experiment a more informal method is used. Participants developed a design task over four weeks, at their normal working places, without being observed or forced to think-aloud. In order to accomplish these requirements the experiment was conducted by post after previous agreement with participants. They were provided with an introductory letter, an A3 sheet with an explanation of the task printed on the top left corner, and a questionnaire placed into another envelop, which participants had to open after the task. The results indicate patterns in the designer's movements between sketches. These patterns have guided construction of a speculative model as the basis for further more formal experiment. .

This informal approach was valuable because participants had the advantage of developing the task in their normal working places without the pressure of being videotaped. Participants had the possibility of breaking up the sketching process in various phases over the four weeks. Further, the fact that participants were provided with an 'official' sheet to sketch on induced some to sketch additional experimental and personal concepts on extra sheets At the end of the task participants were asked to submit all sketches produced during the design process. Eight industrial designers were selected with broad professional experience including consumer products, packaging and urban furniture. All participants had proficient drawing skills.

Participants were asked to devise a design for a new electric jug kettle following a concise brief. They were encouraged to produce at least 10 sketches to come up with a single and preferred proposal. In order to analyse progression in designing, participants were asked to number the sketches as they created them and they were reminded not to erase anything. After completing the task, participants sent back the A3 sheet, and the questionnaire as well as all other representations developed during the design process.

3.2. OBSERVATIONS

Each designer produced on average 20 sketches. Most of these sketches are characterised by overtracing, in which the participant repeatedly outlined a particular shape or area of the sketch. According to Do and Gross (1996), overtracing serves several functions: (i) selection or drawing attention to an element, (ii) shape emergence, attending to one or another shape interpretation, and (iii) shape refinement, or adding detail to an abstract or roughed out shape. The overtracing of sketches has assisted us in identifying where participants change interpretation and detect emergent shapes .

Participants varied the complexity of their sketches through the process. While some sketches had few lines and no details, others were produced with more detail including annotations, shades or hidden lines for example. The hypothesis here is that the level of complexity of sketches reflects the level of abstraction that designers perceive the concept design at that particular moment. The relationship among sketches with different complexity levels will be discussed later. Most participants used brief annotations in their sketches indicating, for example, the position of buttons or the material of a specific part of the kettle. Text was also used by some participants in bubble diagrams or to name concepts, e.g. water drop, bamboo or gourd, identifying their own interpretations of the sketch. Although this study focuses on the shape of sketches, annotations of participants were particularly useful in the analysis of the reinterpretation of concept designs. In addition to reinterpretation, we observed that emergence and abstraction were also salient characteristics that assisted designers in their exploration of designs.

3.2.1 Reinterpretation

Close observation of the sketches reveals features that suggest that participants performed changes of interpretations of their sketches. Changes of interpretation have been identified by comparing the type of strokes used among sketches that represent the same concept design. Van Sommers' (1984) experiments, for example, suggest that there is a strong relationship between design interpretation and the production of strokes. For example, consider the sketches produced in this study by two industrial designers shown in Fig 2a and Fig 2b.

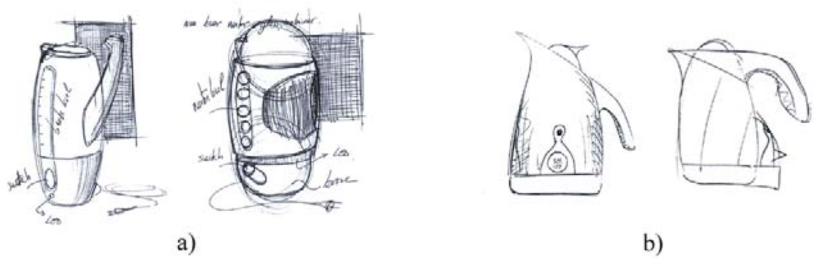

Figure 2. Two sequences of sketches produced by two participants.

The sketches are presented in the sequence they were produced, that is, the sketches illustrated on the right of each pair were produced immediately after the sketches on their left. Fig. 2a shows that, initially, the participant produced the outline of the body and the base of the kettle by continuous strokes, that is, from point 1 to point 2. In the subsequent sketch, the participant drew the base and body by separate strokes. This decomposition between body and base opened to the participant a new range of alternatives. The example in Fig. 2b, shows that initially the participant constructed the spout and body by the same stroke, and in the subsequent sketch, the spout was produced independently from the body. Again, this suggests that the participant changed their initial interpretation of the concept. Note that the sketches produced after Fig. 2a and 2b (not illustrated here), the body, base and spout were repeatedly produced by separate strokes.

Similar examples occured in the sketches produced by other participants. Generally, although not always, changes in the production of strokes occur at intersection points; for example, between the spout and body, handle and body, spout and lid. The decomposition or grouping of elements appears to influence the way subsequent ideas are developed. Once participants had visually decomposed their sketches into a particular set of elements, these decompositions were kept while vertical transformations were performed. Generally, a change of interpretation leads to a lateral transformation where the design is reframed and a new range of alternatives is originated.

Lateral transformations and vertical transformations cannot always be identified by observing shape modifications; sometimes it is necessary to involve the designer's interpretation. For example, Fig 3a shows a concept design on the left side of the arrow, and its modification on the right side.

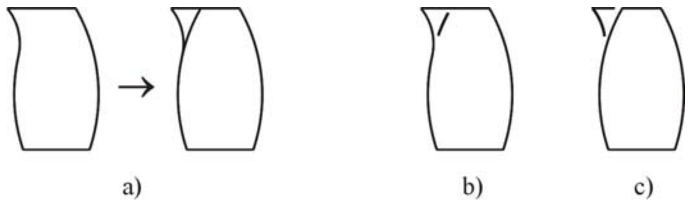

Figure 3. (a) A shape modification, (b) modification interpreted as vertical a transformation, (c) modification interpreted as a lateral transformation.

Is this a lateral transformation or a vertical transformation? The answer is that both transformations can be considered. If the interpretation (Fig. 3b) is that a small line has been added to the original concept design then it is a vertical transformation because the new line is considered as an insertion of detail to the original idea. However, if the interpretation (Fig 3c) is that the added line is an extension of the body's contour then it is a lateral transformation because this movement leads to a slightly different idea compared to the original version. Observe that the original concept design cannot be considered symmetric, and this lack of symmetry is inherited by Fig. 3b. However, the interpretation in Fig. 3c can be seen as symmetric because the spout becomes a detached element from the symmetric body.

Both designs, shown in Fig. 3b and Fig. 3c, are interpreted as the composition of the same parts; body and spout. However, reinterpretation of shapes often leads to the discovering of emergent parts. While emergent shapes are detected because of a reinterpretation of the design, not all reinterpreted designs lead to emergence, as shows Fig. 3.

3.2.2 Emergence

Designers often perceive emergent features in their sketches that may not have been initially intended. In this experiment shapes emerged from both interpretative processes where emergent shapes are embedded in the outlines of the design, and transformational processes where emergent shapes are visually suggested by the outlines of the design but they are not graphically represented (Soufi and Edmonds 1996). Consider Figure 4 for example where the top row shows sketches generated by one of the participants and the second row shows schematic representations used as explanatory illustrations.

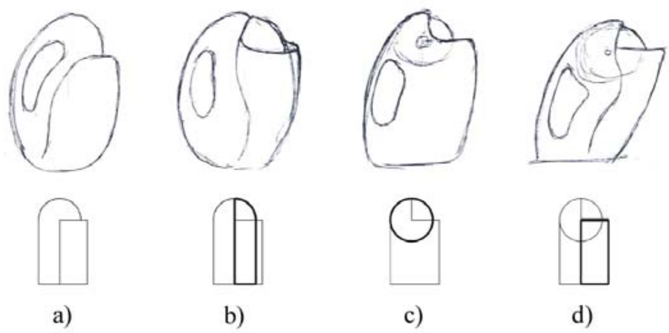

Figure 4. (Top row) Sequence of sketches, (second row) schematic representations of the sketches which highlights emergent features.

The sketch in Fig. 4a may be perceived as a composition of two elements, as illustrated in the schematic representation. In the subsequent sketch (Fig 4b), perhaps because the designer focused on functional aspects such as the introduction of a lid on the top part of the kettle, a new element emerged. This suggests that the central line of the initial concept has been extended in order to respond to an emergent interpretation. The thick line in the schematic outlines the emergent shape. The following sketch, shown in Fig. 4c, suggests again the emergence of a new element. The semi-circular shape on the top of the kettle is now replaced with a complete circle. In sketch shown in Fig. 4d, the designer reinterprets an element that was initially perceived, but which disappeared during the process. The schematic shows the re-emerged element.

This example shows how designers take advantage of emergent shapes, especially from transformational processes. Furthermore, it illustrates that the creative process is not a linear process, and that often designers rely on the exploration of several alternatives in order to make a decision.

3.2.3 Levels of abstraction

Ambiguous and vaguely detailed sketches are not only employed in the preliminary design phases, but they are also during refinement phases. Once designers obtain a promising and detailed concept design, they often step back to higher levels of abstraction in order to explore and evaluate the idea from its essence, and omitting irrelevant constraints. Liu et al. (2003) discuss three levels of abstraction, namely topological solution, spatial configuration and physical embodiment levels. While in the first and second levels concept designs are represented with diagrams such as 'bubble' charts, in the physical embodiment level, concept designs are represented in terms of shapes. Although the three levels are related this paper only deals with physical embodiment levels of abstraction.

Designers generate sketches at different levels of complexity. Generally, there is a correlation between the level of abstraction and the complexity of sketches. The lower the complexity, the higher the level of abstraction, and vice versa. Here, the complexity of sketches is not measured in terms of shapes but in terms of types of information provided by the sketch. McGown and Green et al. (1998) developed what they termed a 'complexity scale' to facilitate a measure of each sketch's degree of transformation according to qualitative judgements. The most simple of the sketches is rated 'one' and the most complex is rated 'five'.

Using this scale, the sketches in this study ranged from complexity level one to complexity level three. It is observed that most participants progressed with an oscillating search approach, where the complexity of the sketches fluctuates according to the aspects of the design being considered at each moment. Consider, for example, a sequence of sketches generated by one participant shown in fig 5 in the order they were produced from left to right. Note that the participant generated more sketches, between those illustrated in Fig. 5, which are not considered here. Using McGown and Green's scale, the sketches illustrated in Fig. 5a and 5d are rated as complexity level 2 because they have annotations and shadings. The sketches in Fig. 5b and 5c are rated as complexity level 1. Overall the sequence of sketches shows an oscillating exploration process, in terms of complexity/abstraction.

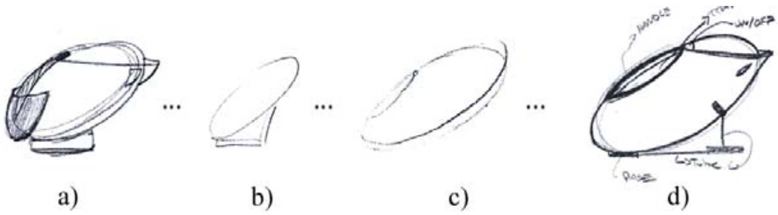

Figure 5. Exploring designs at different levels of abstraction.

The sketch in Fig. 5b suggests focus on the exploration of bases or supports for the kettle. The sketch in Fig. 5c suggests exploration of the positions and types of handles. Both explorations were further developed in more detail in the sketch shown in Fig. 5d. In this experiment, while some low complexity level sketches are not related to previous sketches, that is they arose from divergent thinking, other sketches preserve similarities with previous concept designs at a higher complexity level. In summary, designers proceed by moving backwards and forwards across different levels of abstractions.

3.3 DESIGN FAMILIES

In the previous section it has been discussed how designers engage in reinterpretation, emergence, and abstraction throughout the initial stages of product design. These three cognitive strategies appear to be crucial in design generation. All participants in this experiment made use of them to different degrees in generating creative concept designs. Goldschmidt (1994) argues that designers rarely produce single and isolated sketches, rather they generate sketches in successive spells. Reinterpretation, emergence and abstraction not only give rise to new groups of designs, or design families, but they also assist in exploring them. This section attempts to identify where boundaries might lie between design families and the relationships among concept designs that belong to the same family.

Providing a clear definition of a design family is not easy. Broadly defined, a family is a 'group of related things' but these relations for designs are fluid, depending on reinterpretation, emergence and abstraction by the designer. As it has been often observed in the experiment, two concept designs may appear visually different but the participant may claim that they belong to the same group, and vice versa. This occurs because a design family can be explained, that is the relationship between elements identified, by using different criteria. Imagine, for example, the shape of a kettle and a saucepan. Although they are visually different, they might be grouped in the same design family as both artefacts can be used for warming up water. Here, in order to constrain the definition of design family, ‘things’ is replaced by ‘shapes’. Thus the definition now becomes ‘a family is a group of related shapes’. But, what type of shape relations constitutes a design family? In Goel’s (1995) terms, modification of a shape results from either a lateral transformation or a vertical transformation. While in a lateral transformation movement is among different ideas, a vertical transformation movement is among similar ideas. We narrow the definition of family to be 'a group of vertically transformed shapes’. That is, concept designs generated from lateral transformations, such as the designs illustrated in Fig. 4, are not considered a design family, rather each design offers a point of departure, via vertical transformations for exploration of a new design space. In practical terms families are generated designs within a ‘design’ space of possibilities. Thus a family consists of generated designs whilst the space in which the family lies represents potential generations. For simplicity the space and family may be identified, but it should be noted that the space is defined intensionally by rules whilst the family is defined extensionally by its instances.

Design families contain similar objects, although the kind of similarity is distinguished from similarities based on shared features (Tversky 1977). The relations between designs in a family are transformations of the shape features. Relations among elements in a family are reflexive and symmetric but not necessarily transitive. They are formal similarity relations.

The boundary of a family to which a design belongs depends on the transformation rules. Changing the rules alters the extent and boundaries of the family. Constraining rules contracts the boundaries whilst generalising rules extends them. Movements through the design spaces observed in the previous section can perhaps be illustrated best by keeping boundaries fixed and showing how movement within and between spaces is possible. Consider the movement in Fig. 6 starting from an initial concept design identified as lying in a family A. Immediately this initial concept is reinterpreted (a lateral transformation) as belonging to another family and exploration proceeds through vertical transformations in this space B, until another reinterpretation shifts to the final concept in another space C.

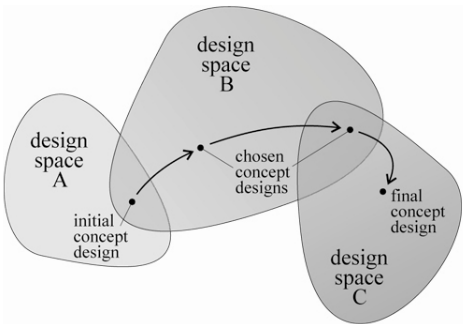

Figure 6. Moving between design spaces.

In practice, designers rarely apply one type of transformation at a time, but lateral and vertical transformations may be carried out concurrently in just one movement. Consider, for example, Fig. 7 which illustrates two design families. Note that the designs are presented in the sequence they were generated, but the original arrangement has been modified. The first design family, Fig. 7a, suggests that the participant was concerned with the curves that characterize the outline of the kettle, and at the same time he was also concerned with several details. Consider now the sequence in which the base of the kettle has been explored. The upper part of the base in the first sketch in Fig 7a is represented with a convex curve, which is then replaced with a concave curve perhaps suggested by the intersection between the body and base. At this point, the resultant type of base was used to frame the bases generated in subsequent sketches. However, not all design families are generated by manipulation of outlines. Designers may also apply combinatorial strategies by adding or deleting certain features. Consider, for instance, how the lid of the kettle is explored in the sequence in fig 7a. The first design does not have a lid, the second has a lid with a lever added, then, in the following design the lever has been removed, and in the last design only the lever has been considered.

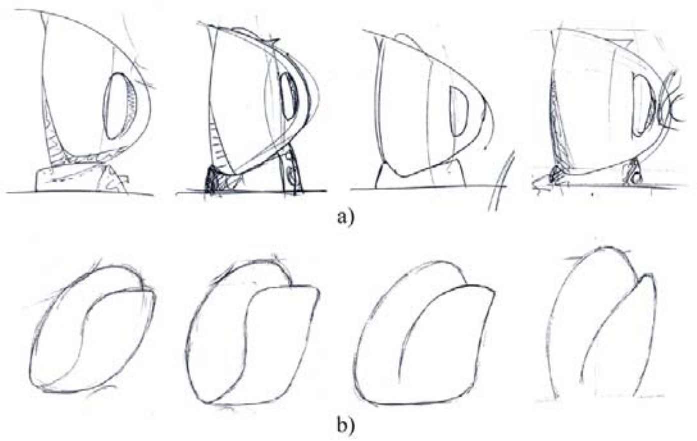

Figure 7. Two sequences of sketches produced by two participants. Each sequence is here referred as a design family.

The design family shown in Fig. 7b has been generated from a higher level of abstraction. The sketches do not have detail which suggests that the participant, at this phase, was focused on the global appearance of the object, and perhaps paying little attention to detail issues. In this design family the participant framed the problem of stability, in the sense of maintaining the object in upright equilibrium, by adopting the strategy of flattening the bottom part of the kettle. These two design families also demonstrate that small variations to the curves can produce a significant impact on the appearance of the design.

Having analysed the results of the experiments in terms of the three cognitive categories of interpretation, abstraction and emergence the paper now models the exploration at early design phase as a more formal process. On the one hand this is aimed at understanding the process of design exploration and on the other hand it offers the basis for a design tool to help exploration.

4. A formal process for exploring designs

The model of exploration is centred on the generative activities of creating new designs. Concentrating on shape and associated drawings as the medium for exploration, the transformations can be represented by shape transformation rules. The terminology of one formalism, namely shape grammars, will be adopted here. Although, many shape grammar implementations have tried to set down generative specifications for styles (McCormack, Cagan et al. 2004) or coherent sets of designs, the free flowing exploratory capabilities of shape rules are rarely developed. Many existing implementations concentrate on vertical transformations although generation at different levels of abstraction is illustrated in the generative optimisation of building structures (Shea and Cagan 1999) which uses both topological and shape transformation rules. However, shape rules (Stiny 1980; Stiny 2006) have wider potential to bridge the gap between traditional sketching techniques and modern computational methods of design. For example current research by the authors considers how shape rules for curved shapes can be implemented and applied to product design. (Jowers, Prats et al. 2004; Prats, Jowers et al. 2004). This section describes how shape rules of various forms can model the cognitive processes of interpretation, emergence and abstraction associated with exploration with drawings and sketches at early design stages. To do this an abstract example is used of generating shapes. These are aligned strongly with the kind of product sketch observed in section 3 and illustrate how the various shape rules work without being tied to a particular product and its associations. In section 5 shape rules are formulated for some of the exploratory processes on the jug kettle described in section 2.

4.1 EXPLORING DESIGNS

The exploration process not only consist of refining or adding detail to kernel ideas but also reinterpreting and the exploration of new paths. The transformation from one concept design into another can be in myriad different ways. In order to guide the exploration process designers frame the possibilities according to their design intentions and interpretations. A shape decomposition is used to represent a designer's personal interpretation of sketches, and shape rules represent a designer's intentions.

This model suggests potential areas for computer support in exploring concept designs. These include the application of generative shape descriptions to explore designs that are consistent with designers' perceptions. The model also provided insights into product design processes and indicated where computational tools might be useful.

The examination of a particular design space is often unachievable because the number of alternatives to consider may be impossibly large. One way of exploring design spaces is through generation of design families within the space. For example consider Fig. 8 as an initial concept design.

Figure 8. Initial concept design

This initial shape is open to a wide choice and interpretations. For example, the circle may be formalized by the rule 1 shown in Fig. 9. A circle is added to the design whenever three connected arcs –with certain conditions– are found. Note that both sides of the rule are parametric. The concern of how parameters are described is not within the scope of this paper.

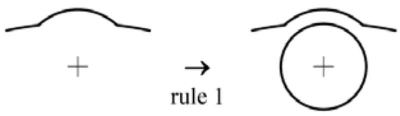

Figure 9. Shape rule for inserting a circle.

The remaining outlines of the initial shape may be formalized by placing decomposition points and decomposition lines. A shape decomposition identifies the limits of each perceived element with breaking points or *decomposition points*. Each element can be represented by a decomposition line, which joins its two extremities. Decomposition lines are non-terminal shapes that assist the formulation of the shape rules but are not part of the final design. This shape or diagram of elements represented by the decomposition points and lines represents the structure of the perceived elements. Significantly it also indicates where to explore shape modification of elements and, further, new arrangements of the elements. A possible decomposition is shown in Fig. 10.

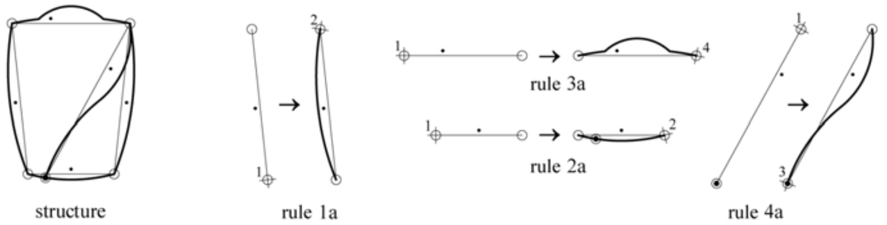

Figure 10. Structure and decomposition rules define the initial concept design.

The initial shape is decomposed into five elements of which two are defined by the same rule. Adjacent to the decomposition lines are labels that ensure that each rule is applied in the right place and in the right position. Observe that one decomposition point in rule 4a is labeled, indicating that this point is attached to the outline in rule 2a. Thus rule 4a relies upon rule 2a.

New designs are generated by manipulating the parameters of the rules, that is, the radius of the arcs are modified as well as the lengths and angles between arcs in rule 3a and rule 4a. A design family is shown in Fig. 11.

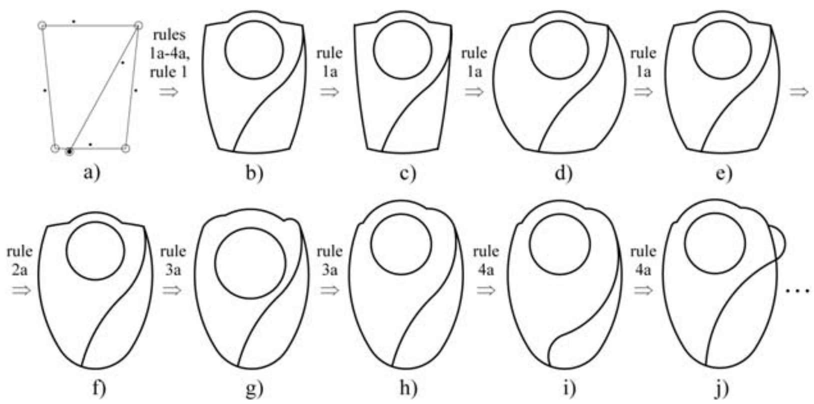

Figure 11. (a) Structure assigned in Fig. 10, (b)-(j) manipulations of the outlines through decomposition rules result in a design family.

The parameters can be randomly modified according to constrains defined by designers (Prats, Jowers et al. 2004). In order to make the generative process more understandable the rules are applied one at a time. For example, in Fig. 11b the rules 1a-4a and rule 1 are applied to the decomposition lines. In Fig. 11c-11e only the rule 1a is applied, in Fig. 11f rule 2a and so on.

It is interesting to observe that small variations on the outlines produce significant perceptual consequences to the initial concept design. These variations assist explorations of designs that are consistent with the interpretation formalized. Each generated design in a family preserves the original structure, or *structural skeleton* as referred by Arnheim (1974). The designs in a family maintain a designer's 'frame' even if outlines are modified randomly by computers.

4.3.1 Emergence

In our empirical study it has been examined how unexpected shapes emerge in the designer's eye during the conceptual stages of design. Stiny (1980) has proposed a method that supports computation of emergent shapes. He argues that shapes do not have finite numbers of parts and therefore can be freely decomposed. Thus emergent shapes can be recognized at any stage of the computation. The history of emergence and formal devices for computing with emergence and ambiguity are discussed in (Knight 2003a,b). Emergent shapes can appear in two ways: (i) application of a defined rule in an unexpected place, and (ii) the designer defines a new rule after perceiving an emergent shape. The examples in Fig. 12 show how the defined rule 1 can be applied to unexpected places.

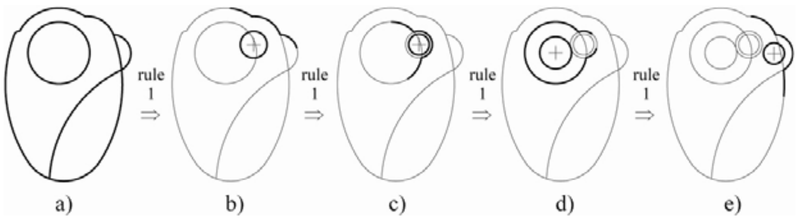

Figure 12. Four different matches of rule 1 on the same design.

4.3.2 Reinterpretation

During the exploration process it is possible to obtain many different designs whilst preserving a particular interpretation of the design. Each design alternative emerges after application of vertical transformations to the concept design. This type of transformations is crucial when designers want to explore versions of a chosen concept design while its essence is kept. However, as seen in the experiment, changes on the interpretation are also crucial in exploration stages. This assists designers in reframing the design space which leads to consider new design alternatives that previously were not taken into account. Consider for example Fig. 13. This new decomposition can generate designs that were unachievable through the previous decomposition.

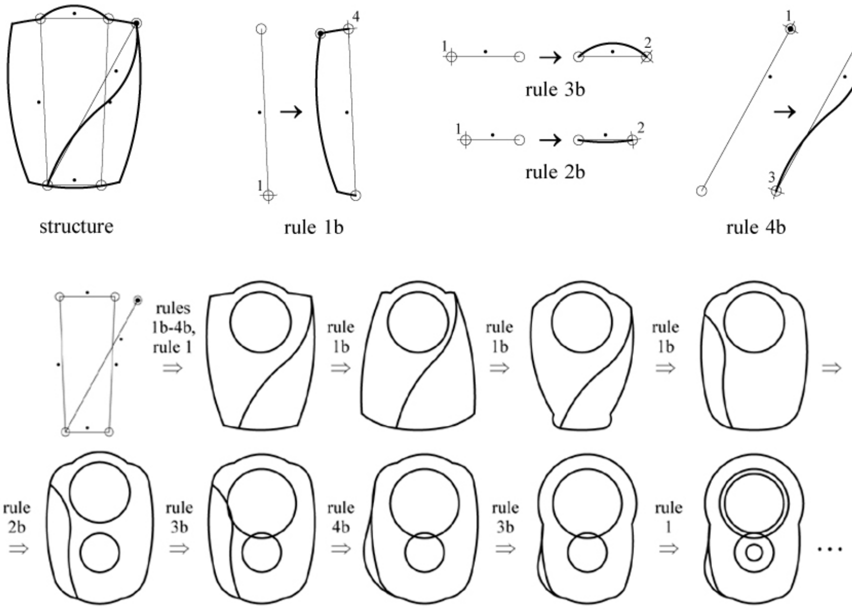

Figure 13. (Top) New structure and rules define the initial concept design (a)-(j) new design family.

4.3.3 Levels of abstraction

One important aspect of the creative process is that shapes can be perceived and represented at different levels of abstraction. During the design process, designers may explore designs at a detailed level by focusing on specific outlines of the shape while temporarily ignoring other outlines. Also, designers may explore designs at a more abstract level by focusing on the arrangement of the elements perceived in the shape. For example, manipulations of decomposition lines, as shows first row in Fig. 14, generate new alternatives of a chosen concept design (in this case Fig. 12d). Note that both rows represent the same design, but in the first row the layer of outlines is not represented, and in the second row the layer of decomposition lines is not represented.

The transformations of the structure are performed in order to satisfy design intentions in an overall sense. In fig 14 the design's structure is approximated into a golden rectangle (Fig. 14b), a square (Fig. 14c), or any other interesting type of shape (Fig. 14d and 14e). Note that once a promising structure has been found all previous designs – design families in

Fig. 11 and Fig. 12 – and also potential designs in the associated design spaces with the same shape rules can be adapted to the new structure. As mentioned earlier, exploration of designs not only consists in manipulating visible outlines, but also examining hidden structures to find internal coherence in designs.

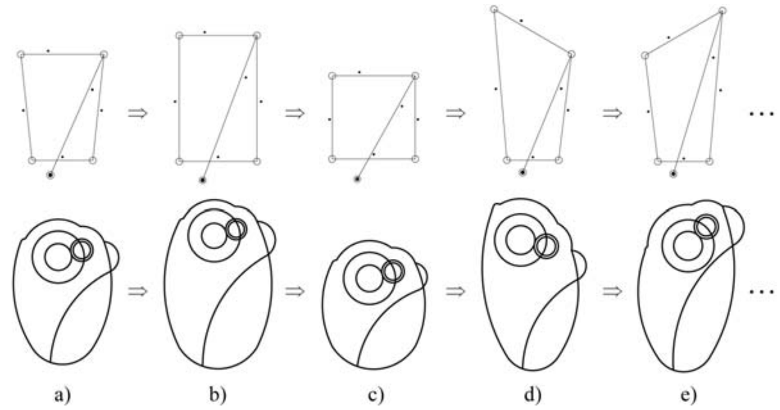

Figure 14. (Top row) manipulations of the structure in Fig. 10, (second row) outlines attached to structures.

5. Discussion

This paper started by examining the role of visual perception in design exploration. Our examination has focused on three perceptual processes which appear to be essential in the exploration of new designs; reinterpretation, emergence and abstraction. We propose that assigning particular structures to designs assists exploration of new designs. In addition, structures may ensure that computationally generated designs are consistent with the designer's perceptual processes. Structures are defined according to designer's perceptions and intentions. Consider for example the sketch in Fig. 15a, which has been taken from our empirical study (See Fig. 2b).

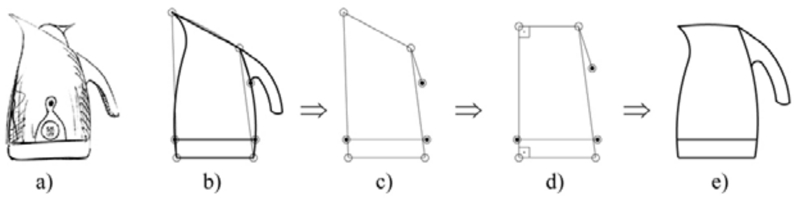

Figure 15. Manipulation of a design.

According to the process presented in this paper, the design can be decomposed by assigning decomposition points and decomposition lines as shown in Fig. 15b. The added lines take the form of a structure (Fig. 15c), which can be manipulated according to aesthetic preferences. A rule (not illustrated here) that arranges two connected lines into a right angle generates the structure shown in Fig. 15d. This is just one possibility from a range of configurations, as previously illustrated in Fig. 14. Fig. 15e shows the outlines attached to the modified structure.

New elements of detail may be added to this design as shown in Fig. 16a. If the introduction of these elements is defined in terms of shape rules they may generate additional designs as previously illustrated in Fig. 12.

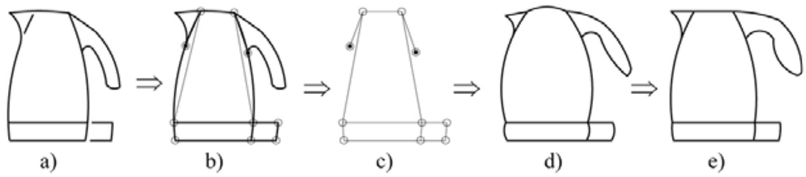

Figure 16. Reinterpretation of the design in Fig 15 and manipulations of outlines.

Once the elements are in place an inspection of the design may suggest new interpretations. Fig. 16c shows a possible structure defined according to a new reinterpretation. Design alternatives can be explored by modifying the outlines defined by the structure. Fig. 16d and 16e show two examples.

With the purpose of inserting a lid in the kettle a new rule could be defined. For example, two symmetrical curves are found (shown in thick line in Fig. 17a) and they are joined with an arc from their end points as shows Fig. 17b. However, this rule can find more instances in the design which generate unexpected designs that may provide emergent features as shows Fig. 17d. Observe the similarities between this design and the sketch in Fig. 17e taken from our empirical study.

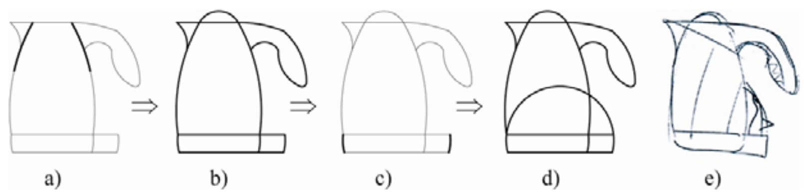

Figure 17. Insertion and emergence of new features.

This example attempts to show that sequences of designs, at least in convergent thinking, can be traced in a systematic and logical way. Here we have traced a path that formalizes the sequence of modifying one sketch

(Fig. 15a) into another (Fig. 17e). This path has been constructed by means of using reinterpretation, emergence and abstraction as examined in our empirical study. In the experiment the designer produced these sketches in one single step, but the parallelism between imagery and perceptual processes discussed by Kosslyn (1990) bring us to the hypothesis that the designer followed a mental process comparable to the path shown in Fig. 15-17. The evidence of the sketches suggests that the cognitive processes of reinterpretation, emergence and abstraction are widely used. These are expressed in terms of shape rules in an associated model. Further work is being undertaken in implementing the kinds of shape rule on curved shapes that are required for product design.

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