The cognitive basis of emergence: implications for design support

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Emergent shapes play a significant role in the creative design process. Designers frequently visualize emergent shapes and structure their understanding of the design and their reasoning about it in terms of emergent entities and relations. In design research, effort has concentrated on developing computational models capable of representing emergent shapes. Much less attention has been paid to the cognitive processes that give rise to emergence. In cognitive science, however, emergence has been the subject of empirical study. It is suggested that both the study of perception and that of mental imagery can contribute to understanding the cognitive psychological basis of emergence and the nature of emergent shapes that arise. Relevant cognitive science research findings are reviewed in this paper. Based on these findings two main classes of emergence processes are developed. Their implications for the development of user-interactive computational models of emergent shapes are then discussed. Copyright © 1996 Elsevier Science Ltd.

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In design, drawing and sketching have traditionally been used as the primary mechanism for externalising the ideas of the designer, and subsequently for analysis and reconsideration of these ideas. Recent studies of design[1,2] suggest that design proceeds through half-formed and ill-articulated concepts. According to Fish and Scrivener[3] an important feature of sketches is that they contain uncertainties important to their function and play the role of preserving alternatives. In line with the same view, Mitchell[4] states that 'drawings are valuable precisely because they are rich in suggestions of what might be . . . thus the meaning of a drawing is not adequately captured by imposing one structure on it'.

Current computer-aided design systems do not provide sufficient support to the early conceptual stages of design. They have replaced hand-drawing

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1 **Neilson, I E and Lee, J R** 'Conversation with graphics: implications for the design of natural language/graphics interfaces', *International Journal of Human-Computer Studies* Vol 40 (1994) pp 509–541

2 **Lee, J R** 'Graphics and language in design and instruction', in **R J Beun, M Baker and M Reiner** (eds) *Dialogue and Instruction* Springer-Verlag, Berlin (1994)

3 **Fish, J and Scrivener, S** 'Amplifying the mind's eye: sketching and visual cognition', *Leonardo*, Vol 23 No 1 (1990) pp 117–126

4 **Mitchell, W J** 'Introduction: a new agenda for computer-aided design' **M McCullough, W J Mit-**

techniques only in the more detailed and routine aspects of design. Scrivener[5] argued that such systems require designers to pregeneratively structure a computer image and then limit understanding and manipulation to this structure. Consequently, they are inappropriate to the early creative stages of design during which ideas are often vague and incomplete, as are their drawn representations.

1 Computational modes of emergent shapes in design

Emergent shapes arise as a result of the use of visual representations of design and the interaction with these representations. This plays an important role in directing design exploration. The need for CAD systems to better respond to designers in structuring and manipulating emergent shapes is a primary motivation for research into the computational modelling of emergence.

A key feature of computational models is the representation of shape in a manner that allows emergent shapes to be obtained. It is noted that the transformation of shape through different types of representation is a theme shared by several models. Edmonds and Soufi[6] have highlighted the role of creative perception in early design and the need to support this process by a computational approach that arrives at perceptually valid emergent shapes.

The implications of emergence for systems supporting collaborative design have been discussed by Edmonds *et al.*[7] They proposed an agent-based approach that can handle the different types of knowledge required. Since emergence allows for the introduction of new concepts, behaviours and functions it has impact not only on knowledge syntax but also on its semantics.

The development of appropriate representations is also a concern of many researchers. Gero and Yan[8] have described a symbolic computational model of shape emergence based on infinite maximal lines. Using this representation, and by removing/replacing constraints, emergent shapes can be discovered using both hypothesis-driven and data-driven searches. Gero and Damski[9] extended the above approach to three-dimensional shapes where a representation based on infinite maximal planes is used to represent three-dimensional shapes. Liu[10] has proposed a connectionist approach to the encoding of shapes. Based on the operations of trained connectionist networks, emergent shapes can be encoded by the system. A searchlight mechanism is used to derive emergent shapes within a selected grid.

chell and P Purcell (eds) *The electronic design studio*, MIT Press, Cambridge, MA (1990) pp 1–16

[5] **Scrivener, S A R** 'The interactive manipulation of unstructured images', *International Journal of Man-Machine Studies*, Vol 16 (1982) pp 301–313

[6] **Edmonds, E A and Soufi, B** 'The computational modelling of emergent shape in design', in **J S Gero and F Sudweeks** (eds) *Computational models of creative design*, University of Sydney, Sydney, Australia, 1992, pp 173–190

[7] **Edmonds, E A, Candy, L C, Jones, R and Soufi, B** 'Support for collaborative design: agents and emergence', *Communications of the ACM*, Vol 37 No 7 (1994) pp 41–47

[8] **Gero, J S and Yan, M** 'Shape emergence by symbolic reasoning', *Environment and Planning B: Planning and Design* Vol 21 No 2 (1994) pp 191–212

[9] **Gero, J S and Damski, J C** 'Object emergence in 3 D using a data driven approach', in **J S Gero and F Sudweeks** (eds) *Artificial Intelligence in Design 94*, Kluwer, Dordrecht, The Netherlands (1994) pp 419–435

[10] **Liu, Y T** 'Encoding explicit and implicit emergent subshapes based on empirical findings about human vision', in **J S Gero and F Sudweeks** (eds) *Artificial Intelligence in Design 94*, Kluwer, Dordrecht, The Netherlands (1994) pp 401–418

Each of the computational models described above is concerned with the employment of a representation that can lead to emergent shapes. Soufi and Edmonds[11] have presented a framework for the computational modelling of emergent shapes based on multiple shape representations.

Other approaches relevant to the construction and visualization of shapes are those of Stiny[12,13], and Krishnamurti and Stouffs[14]. They are more concerned, however, with the representation of shape using shape algebras than with emergence.

2 *Emergent shapes in design and psychology, a closer examination*

Descriptions of emergence in design drew upon parallel psychological theories. One concern of the study of perception is understanding the way in which sensory information is transformed into an organized model of the world. The information gained from the optical array is not, by itself, sufficient to give a meaningful description of the scene. In other words, the visual system constructs a model of the world that exceeds, in its information content, the proximal stimulus. This phenomenon has been extensively studied by psychologists and different accounts have been motivated[15].

Another concern is the study of how mental images are represented and synthesized. Reed[16] has conducted experiments the findings of which supported the notion of structural descriptions. This suggests that a given pattern may have a number of associated interpretations. Further work in this area showed that humans can synthesize and combine mental images in a variety of ways[17,18].

It is suggested that emergent shapes in design are not only the result of perception constructing a model of the world but also a consequence of transforming the world. This view of emergence is necessary if we are to account for certain emergent shapes that do not exist in the model of the world as represented by the original stimulus pattern. Since this view of emergence has commonalities with accounts of creativity based on transformation of conceptual spaces (e.g. Boden[19]), it supports the assertion that emergence is creative[20,21].

Given this view of emergence, how does this impact on the development of a computational model that supports arriving at emergent shapes which arise in such a manner? Two processes are implied: firstly, an interpretative, perceptual, process concerned with arriving at (alternative) entity

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[11] **Soufi, B and Edmonds, E A** 'A framework for the description and representation of emergent shapes', in **M Tan and R Teh** (eds) *The Global Design Studio, Proceedings of CAAD Futures 1995*, National University of Singapore, pp 411–422

[12] **Stiny, G** 'Introduction to shape and shape grammars', *Environment and Planning B*, Vol 7 (1980) pp 343–351

[13] **Stiny, G** 'Emergence and continuity in shape grammars', in **U Flemming and S Van Wyk** (eds), *CAAD Futures '93*, Elsevier, Amsterdam, pp 37–54

[14] **Krishnamurti, R and Stouffs, R** 'Spatial grammars: motivation, comparison, and new results, in **U Flemming and S Van Wyk** (eds), *CAAD Futures '93*, Elsevier, Amsterdam (1993) pp 57–74

[15] **Rock, I** 'The description and analysis of object and event perception', in **K R Boff** (ed), *Handbook of perception and human performance*, Wiley, New York (1986)

[16] **Reed, S K** 'Structural descriptions and the limitations of visual images', *Memory and Cognition*, Vol 2 No 2 (1974) pp 329–336

[17] **Kosslyn, S M, Farah, M J, Fliegel, S L and Reiser, B J** 'Generating visual images: units and relations', *Journal of Experimental Psychology: General*, Vol 112 No 2 (1983) pp 278–303

[18] **Finke, R A, Ward, T B and Smith, S M** *Creative cognition: theory, research, and applications* (1992) MIT Press, Cambridge, MA

[19] **Boden, M A** *The creative mind: myths and mechanisms* Weidenfeld and Nicolson, London (1990)

[20] **Gero, J S** 'Computational models of creative design processes', in **T Dartnall** (ed) *Artificial intelligence and creativity*, Kluwer, Dordrecht, The Netherlands (1994) pp 269–281

[21] **Mitchell, W J** 'A computational view of design creativity', in **J S Gero and M L Maher** (eds) *Modelling creativity and knowledge-based creative design* Erlbaum, Hillsdale, NJ (1993) pp 25–42

descriptions of a pattern and; secondly, a transformational process that uses the existing pattern as a prompt for generating new structures in a variety of ways.

The interpretative process is constrained, and for a given pattern, the possibilities generated are limited and predictable. The constraints that influence this process have been described by the Gestalt psychologists[22]. The transformational process, by comparison, is unconstrained and for a given pattern can potentially lead to a large and unpredictable set of possibilities.

A computational model that embodies the above view of emergence should support both processes. The set of possibilities accounted for by the interpretative process should be realizable computationally. The set of possibilities accounted for by the transformational process would, however, be much more difficult to arrive at computationally. This is to be expected because of the unpredictability of this process. Notwithstanding any such difficulty, the computational modelling of emergence remains an important aspect of supporting creative design. This support can be achieved by providing tools that respond to, and augment, the creative process of designers rather than automate it. Therefore, a computational model of emergence is useful even if it does not account for all possibilities. Furthermore, the computational modelling effort will benefit from utilizing knowledge about designers' cognitive strategies with respect to the transformation process.

2.1 Emergent shapes associated with the two processes

To illustrate the difference between emergent shapes that arise as a result of the two processes, consider the pattern shown in Figure 1. Emergent shapes associated with the interpretative process are shown in Figure 2, those associated with the transformational process in Figure 3. In the figures emergent shapes are drawn with thick lines.

Thus it can be seen that even in the case of the simple example of Figure 1, there are various ways in which emergent shapes associated with a trans-

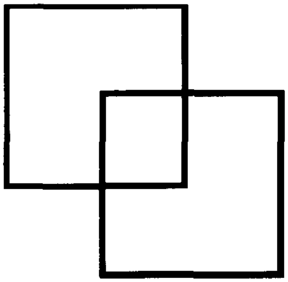

Figure 1 Original shape

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[22] **Ellis, W D** (ed) *A source book of Gestalt psychology*. Routledge and Kagen Paul, Kloisterberg (1938)

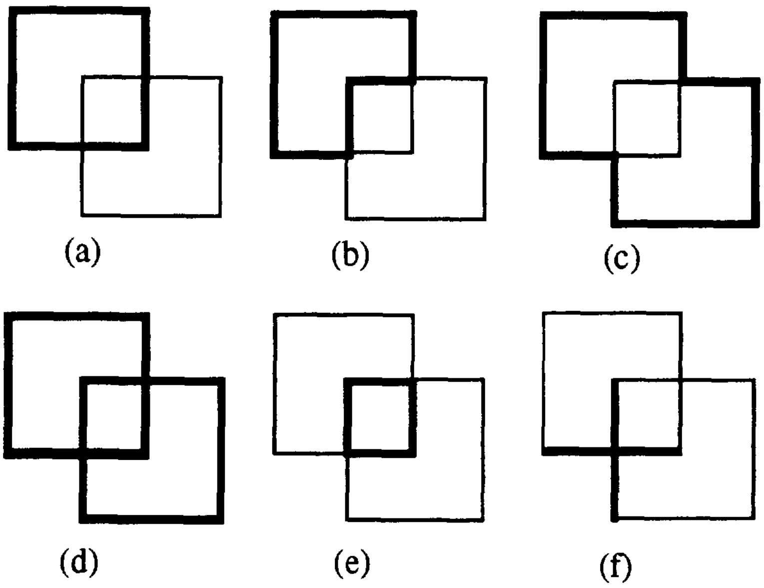

Figure 2 Emergent shapes associated with an interpretative process

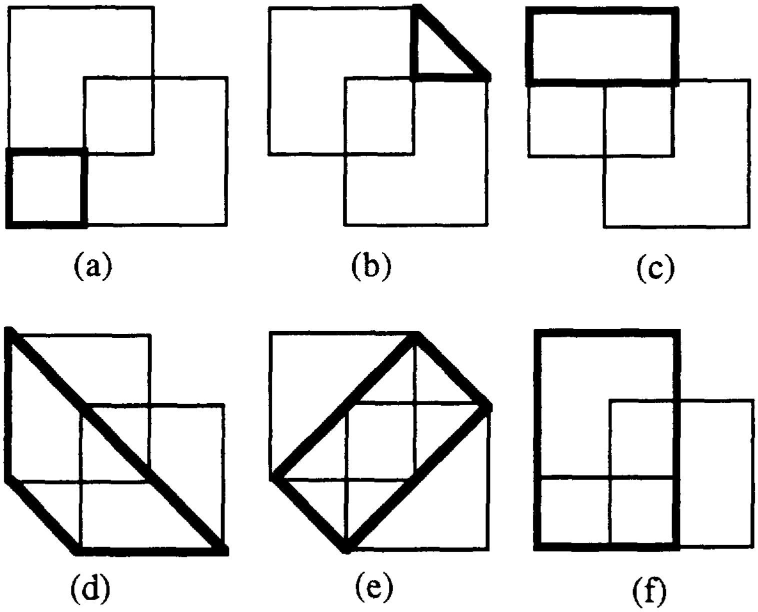

Figure 3 Emergent shapes associated with a transformational process

formational process can arise. They may be parts of a shape (Figure 3c), they may be a result of extending the shapes' boundaries (Figures 3a and 3f), they may also arise as a result of constructing shapes from existing or new end points (Figures 3b, 3d, 3e). Examples of new end points are those that can be obtained by intersections of extended boundaries.

3 Types of emergent shapes

We have distinguished between emergent shapes that arise as a result of the two processes defined above. There have been different categories used by design researchers to describe emergent shapes. For example, Gero and Yan[8] distinguish between shapes that have boundaries which are boundaries of the initial shapes, and those with boundaries that are not necessarily boundaries of the initial shapes. Liu[10] uses the descriptions explicit and implicit emergent shapes. Although no clear definition is given of these descriptions, 'explicit' emergent shapes appear to match those that have boundaries in the original pattern.

A closer examination of emergent shapes suggests the need for a scheme that establishes clearer distinctions between the different types. Building on the descriptions of the two processes that give rise to emergent shapes, there are two distinct types of shapes which may result from the interpretative process.

3.1 Embedded shapes

These are shapes all of whose boundaries exist in the original pattern. Usually, they arise due to the perceptual ambiguity associated with patterns composed of overlapping shapes. This leads to various interpretations. Examples of such shapes can be seen in Figure 2 where all the interpretative shapes shown are embedded shapes.

3.2 Spatially completed shapes

Spatially completed emergent shapes are defined to be shapes that are partially or totally occluded in the original pattern. Unlike emergent shapes that arise due to the transformational process, these shapes can only arise as a result of occlusion. This often occurs in two-dimensional images representing three-dimensional space. The example given in Figure 4 can give rise to the spatially completed emergent shapes shown in Figure 5.

It is more difficult to categorize emergent shapes associated with the transformational process because of its unpredictability. In this case, however, a distinction is made between two types of shapes: firstly, emergent shapes all of whose boundaries are existing boundaries or extensions of existing boundaries; and secondly, emergent shapes that have boundaries which do not exist in the original pattern nor could they have been obtained by extending the boundaries of the original pattern.

4 Requirements for the computational modelling of different types of emergent shapes

Approaches to the computational modelling of emergence[8,23] have used variations on a general model of shape emergence shown in Figure 6.

23 Tan, M 'Saying what it is by what it is like – describing shapes using line relationships', in **M McCullough, W J, Mitchell and P Purcell** (eds) *The Electronic Design Studio* MIT Press, Cambridge, MA (1990) pp 201–214

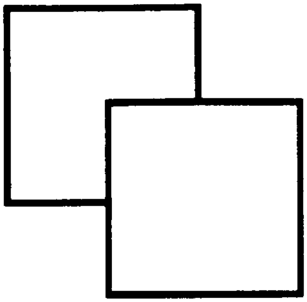

Figure 4 Original pattern exhibiting occlusion

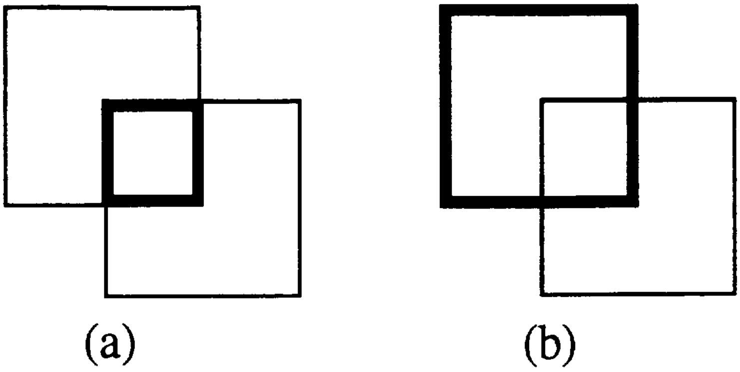

Figure 5 Spatially completed emergent shapes

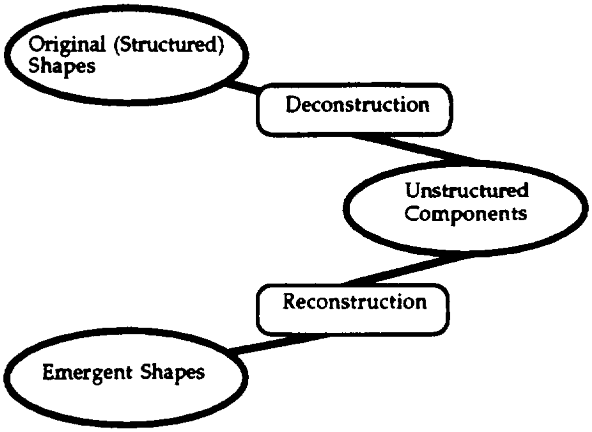

Figure 6 A process model of shape emergence

A key feature of this model is the use of an intermediate representation which enables new shapes to be discovered. The intermediate representation is therefore a richer representation in the sense that it leads to more structures being seen in a given pattern. In the above model, the processes of deconstruction and reconstruction can be seen to be associated with transformations between different representations. The symbolic computational model of Gero and Yan[8] uses a representation based on infinite maximal lines. The computational model of Edmonds and Soufi[6] uses a representation based on regions. Regions are primitive elements grown from pixels using four or eight connectedness[24]. Tan[23] uses a description based on construction lines.

Soufi and Edmonds[25] have argued for the use of multiple representations in the computational modelling of emergent shapes. They showed that certain emergent shapes can be more easily accounted for by using one representation than another. The concept of using multiple representations to describe a particular problem space has similarities to other attempts to model creativity. Savolainen[26] proposed an approach that would allow constructing multiple models of the problem in different representations, and from many different viewpoints. He suggested that by working through the problem in different ways, the user's ownership, motivation and insight are increased, leading to increased creativity.

Further support for the use of multiple representations comes from the earlier assertion that there are emergent shapes associated with the two different processes (interpretative and transformational). It is suggested that no one reconstruction mechanism will be sufficient to account for all these emergent shapes. In any case, a computational model is not likely to be able to capture all the possibilities implied by the transformational process. The above suggests two specific requirements for the computational model. Firstly, it should use multiple shape representations; and secondly, it should use different and parallel deconstruction/reconstruction mechanisms.

5 *Interacting with emergent shapes*

Our proposal for multiple reconstructions implies that a multiplicity of emergent shapes can be derived from a given pattern. Since this work is concerned with supporting the designer's creativity, a key issue is managing the interaction between the designer and the emergent shapes arrived at by the system. Two possibilities need to be considered for this interaction. Firstly, in order to select or manipulate a particular emergent shape that the user is concerned with at a specific time, how can this be specified to the system? Secondly, if the user requires the system to assist by suggesting possible emergent shapes, how can these shapes be presented to the user?

5.1 *User specifies emergent shapes*

This case suggests the provision of a facility that enables the user to specify the emergent shape and its location. This may be achieved by the user providing the system wth a category or description of the emergent shape. An example of a description is one that belongs to a shape vocabulary (a

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24 Rosenfeld, A 'Connectivity in digital pictures', *Journal of the Association for Computer Machinery* Vol 17 (1970) pp 146–156

25 Soufi, B and Edmonds, E A 'Perceptual interpretation and representation of emergent shapes', *Reasoning with Shapes in Design, Workshop Notes, Artificial Intelligence in Design 94*, Lausanne, Switzerland, August 1994, pp 39–45

26 Savolainen, T 'Expanding human-computer interaction by computer-aided creativity', *Interacting with Computers*, Vol 2 No 2 (1990) pp 161–174 square, a trapezoid etc.). It may be necessary to specify the location of the shape and its positional relationship to other shapes since a given pattern may give rise to a number of shapes with the same category.

Existing methods for graphical object selection such as pointing, clicking, and encircling, when used with gesture-based methods of interaction, cannot sufficiently deal with the ambiguity of having a multiplicity of shapes available for selection. This is precisely the issue addressed by Saund and Moran[27] in developing perceptually supported image editing tools. They described two supplementary techniques for gesture-based object selection and a framework for using multiple gesture selection methods simultaneously. The first technique, known as pose matching, makes use of gesture location and shape to indicate the approximate location and elongation of the intended object. The second technique, known as curve tracing, allows the user to select an arbitrarily composed shape by tracing an approximate path over it. The system then identifies the connected collection of line/curve fragments that best matches the specified path.

Saund and Moran[27] have also described a mechanism that allows gesture-based techniques to work independently and in parallel. A confidence measure is used by the system to predict which of the techniques (point and tap, encircling, pose matching and curve tracing) is the best interpretation of the current selection gesture.

These techniques, while based on pen computing, can be adapted to other graphics interfaces. In particular, the technique of pose matching is considered appropriate for mouse-driven systems. Since a pose model of a shape is equivalent to fitting an oriented bounding box around the object, a different and a convenient method of specifying a pose model is the use of visual descriptors of the type described by Charles and Scrivener[28]. They proposed the use of graphical entities, that can be located and combined, in supporting a depictive-descriptive representation of the picture (Figure 7). Graphical descriptors such as these in Figure 7 can be used to specify a pose model of the shape. It is proposed that they can be used in an interactive context to provide a description of emergent shapes (Figure 8).

5.2 *System suggests emergent shapes*

If it is necessary for systems to respond to designers in the specification and manipulation of emergent shapes in order not to impede their creative process, enabling designers to obtain a view with regards to the emergent shapes present would further help this process.

However, since a multiplicity of emergent shapes can arise, it would be of limited use to present the set of emergent shapes to the user. In any

[27] **Saund, E and Moran, T P** 'A perceptually-supported sketch editor', *Proceedings ACM Symposium on User Interface Software and Technology – UIST '94*, Marina del Rey, CA, November 1994, ACM Press, New York (1994)

[28] **Charles, S and Scrivener, S** 'Searching pictorial databases by means of depictions', *Interactive Multimedia*, Vol 2 No 2 (1991) pp 5–16

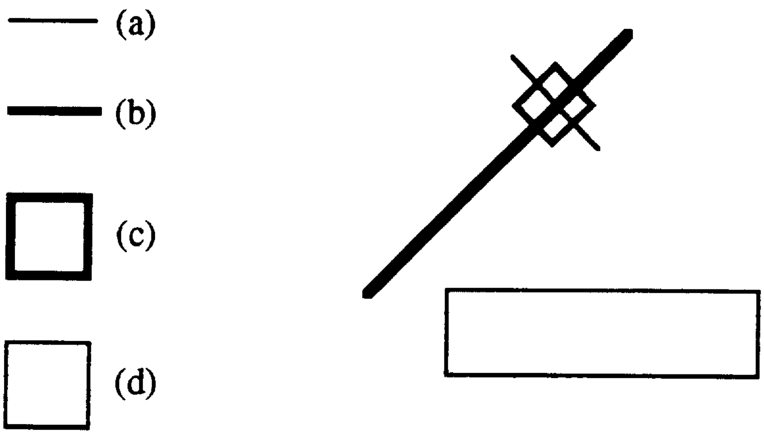

Figure 7 Graphical primitives for depictive-descriptive representations (based on Charles and Scrivener[28]). A thin line a) is used to represent the width of the shape, a thick line b); the length, position and orientation. A thick rectangle c) represents tolerance for the position of the centre of gravity; a thin rectangle d), the size of the shape

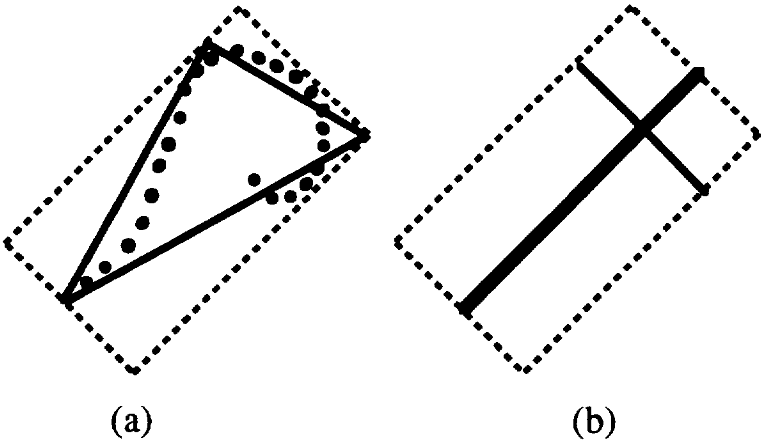

Figure 8 A pose model of an emergent shape (the triangle) can be specified by the pen-based-input technique of pose matching a) and using graphical primitives b). The circular dots in a) represent the selection gesture's path

case, for this type of interaction, it is desirable that the shapes proposed by the system are ones that could have been conceived of by the designer rather than any arbitrarily constructed shapes.

Thus, starting from a potentially huge set of emergent shapes associated with the interpretative and transformational processes described above, can the computational model exploit a selection process that would prioritize emergent shapes? The criteria that will guide this selection process need to capture the difference between emergent shapes likely to be cognitively perceived and those that are not. This issue is of particular significance in the case of transformational emergent shapes since there is a body of psychological knowledge that can be drawn upon to predict what interpretations are possible or preferred in a given pattern[29].

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[29] **Buffart, H, Leeuwenberg, E and Restle, F** 'Coding theory of visual pattern completion', *Journal of Experimental Psychology, Human Perception and Performance* Vol 7 No 2 (1981) pp 241–274

The study of the human visual system suggests that there are two different stages for processing visual input. A preattentive stage characterized by parallel processing of information, and an attentional stage characterized by the serial and location dependent processing. The preattentive stage also acts as a selective stage that directs attentional processes. The traditional view of preattention is that it is limited and that attention is required to arrive at an object description[30]. More recent work[31–33] has shown that the preattentive stage is responsible for the 'pop-out' cases in visual search where the properties of objects are discerned in parallel. Furthermore, Enns and Rensink[34] have reported that preattentive vision is capable of 'interpretative' object completion processes (cf. spatially completed emergent shapes).

A complete account of the mechanisms of visual processing is beyond the scope of this paper. We suggest, however, that similar processes give rise to emergent shapes. One aspect of emergence can therefore be attributed to the effortless pop-out of certain shapes, another to an effortful searching process.

For the purposes of the computational model, if the system is called upon to suggest emergent shapes, it should reflect these cognitively different aspects of emergence. In other words, the shapes proposed by the system should match those that would be expected to pop-out of the image and those that can be arrived at by an effortful searching process. This has the consequences that the computational model should utilize a domain independent part that has knowledge about perception, and a domain specific part that incorporates knowledge of a particular design domain. In this way, the bottom-up nature of pop-out, and the top-down nature of search are reflected in the model.

6 *An overall model for the representation of and the interaction with emergent shapes*

Given the processing and interaction requirements identified above, a proposed model for the representation of, and interaction with, emergent shapes is given in Figure 9. Soufi and Edmonds[11] have described in detail the operation of the model and the roles of the different representations. The following discussion deals with the implications of interaction with emergent shapes generated by the model. Briefly stated, the operation of the model is based on generating structures at two different levels of processing. 'Primary Emergent Structures' are generated by computational mechanisms which operate on multiple representations simultaneously. These are based on 'Line Segments', 'Regions', 'End Points' and 'Pixels'.

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30 **Neisser, U** *Cognitive psychology* Meredith, New York (1967)

31 **Treisman, A and Gelade, G** 'A feature integration theory of attention', *Cognitive Psychology* Vol 12 (1980) pp 97–136

32 **Treisman, A and Gormican, S** 'Feature analysis in early vision: evidence from search asymmetries', *Psychological Review* Vol 95 (1988) pp 15–48

33 **Humphreys, G W, Riddock, M J and Quinlan, P T** 'Grouping processes in visual search, effects with single- and combined-feature-targets', *Journal of Experimental Psychology* Vol 118 No 3 (1989) pp 258–279

34 **Enns, J T and Rensink, R A** 'An object completion processes in early vision', in **A Gale** (ed), *Visual search III*, Taylor and Francis, London (in press)

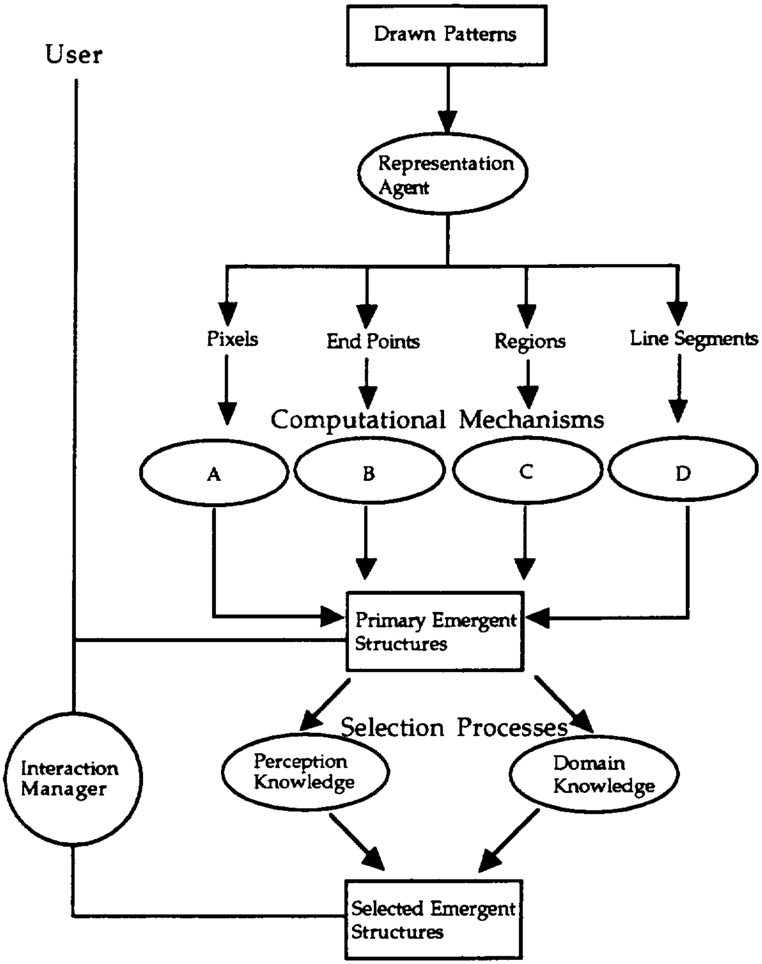

Figure 9 An overall representation and interaction model

The 'Representation Agent' is responsible for creating these representations and enabling transformations between them, given the original shape. The primary emergent structures are the overall set of emergent shapes that can be captured by the model. All these shapes can usefully be made available to the interactive process where the user specifies a particular emergent shape.

'Secondary Emergent Structures' result from the application of selection processes to first-level structures. As discussed above, the selection processes utilize both *domain independent* knowledge about human perception and *domain specific* knowledge of the application domain. This achieves the important function of guiding the computational mechanisms to generate structures that would appear intuitive to the designer because they reflect cognitively valid aspects of emergence. Selection based on knowledge of human perception assigns higher weights to structures that have a sound psychological basis. Selection based on knowledge of the application domain assigns higher weights to shapes indicative of entities that exist in that domain. For this, it is necessary to have knowledge of what a shape may represent in a particular domain and a shape vocabulary in reference to which shapes can be classified.

Therefore, secondary emergent structures with the highest rankings can be presented to the user. This supports the second type of interaction between the designer and the system.

7 *Conclusions*

We have considered the processes that give rise to emergence from both computational and psychological perspectives. Based on a cognitive analysis of emergence, two classes of emergence processes have been described. They have been further elaborated into a scheme for distinguishing between different types of emergent shapes.

Requirements have been identified for a computational model capable of representing these different types of emergent shapes and which supports the user's interaction with them. The computational implications of this interaction have been discussed and appropriate techniques developed to support the proposed methods of interaction. In totality, the model presented in this paper is a theoretical one although certain of the computational mechanisms described have been developed. Edmonds and Soufi[6] have described a mechanism for pixel/region based representations. Gero and Yan[8] have described a mechanism based on line segments. In terms of the selection processes, Soufi and Scrivener[35] have described a system that generates psychologically valid structures; van der Helm and Leeuwenberg[36] have dealt with an automatic approach to shape simplicity. Current research will address the integration of these mechanisms and incorporating the suggested methods of interaction.

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35 **Soufi, B and Scrivener, S A R** 'Perceptual grouping algorithms and object identification', in **A Gale** (ed) *Visual Search III*, Taylor and Francis, London (in press)

36 **van der Helm, P A and Leeuwenberg, E L J** 'Avoiding explosive search in automatic selection of simplest pattern codes', *Pattern Recognition*, Vol 19 No 2 (1986) pp 181–191