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Multiple representations as a platform for situated learning systems in designing

J.S. Gero*, R.M. Reffat

Key Centre of Design Computing and Cognition, Department of Architectural and Design Science, University of Sydney, Sydney, NSW 2006, Australia

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Abstract

This paper introduces the development of multiple representations as a platform for learning design knowledge in relation to the situations within which it was recognised. The benefits of this approach derive from the fact that knowledge is more useful when it is learned in relation to its situation and less useful when it is learned out of context. The situation is the way in which knowledge is located in relation to its surroundings. The situatedness of knowledge is constructed through learning which parts of the surroundings are in conjunction with it across different representations of a design composition. In order to learn the situatedness of design knowledge a medium is needed to present the design composition from different views, each of which allows for various situations to be encountered. What makes multiple representations useful in the context of situatedness is that they provide the opportunities for different and rich relationships among design knowledge to be constructed. This provides a system within which to learn from a number of representations in which the situatedness of knowledge can be discerned and learned. Architectural design compositions are chosen as a vehicle for the demonstration of the concept of situatedness in designing because the discovery of relationships among parts of the design composition is a fundamental task in designing. The paper shows how multiple representations could provide a platform for situated learning systems in designing. What kind of situated knowledge could be learned from some of the possible representations of an architectural design composition is discussed. The regularities of relationships between design knowledge and its situations are investigated. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Multiple representations; Situatedness; Learning in designing

1. Introduction

Recent research into human learning challenges the separation of what is learned from how and where it is learned. The circumstances in which knowledge is developed and deployed, it is now argued, are not separable from or ancillary to learning. Rather they are an integral part of what is learned and learning is fundamentally situated [1]. The research reported in this paper is driven by the situational aspects of designing. Thus, this work is founded on the notion that design knowledge is situated and its use is fundamentally influenced by the situation in which it was recognised. This view of knowledge as situated has important implications for learning design knowledge. The word "designing" is used to refer to the activities of producing a design product. In designing, it is not possible to know completely beforehand what particular set of states the designers would be at and in consequence what kinds of situations might be encountered cannot be predetermined. If all designing states a designer might encounter were known a priori it would have been simple to predefine the appropriate representations that conform to the situations at those states. Thus, learning systems need to learn the design knowledge in focus in relation to its situations within which it was recognised across different representations of a design composition. In order to capture the situatedness of design knowledge a medium is needed to present the design composition from different views to allow for various situations to emerge.

This paper presents multiple representations as a medium or platform for a system to learn design knowledge and its situatedness. The notion of situatedness in designing is applicable to all designing activities and is illustrated here within a visual composition while designing. However, there is much more in designing than geometrical, dimensional and spatial relationships among parts in the design composition. In the domain of architectural design composition, perception occurs more often when designers look at existing depictions than when they draw something [2]. This implies that designers appear to use different representations from what is apparently the same object whenever it suits

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* Corresponding author.
E-mail address: john.rabee@arch.usyd.edu.au (J.S. Gero).

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Fig. 1. The same stimulus is perceived as a H or an A depending on its situation, after [5].

them while designing. In each representation there is the possibility to recognise certain relationships among parts of the design composition that were not explicitly recognisable in other representations. The relationships among parts can be geometrical and non-geometrical in nature. These relationships are called shape semantics and also referred to as design knowledge. Hence, multiple representations provide a mechanism that encourages reinterpreting existing depictions and presents what is depicted in different ways whereby emergent shapes, shape semantics and relationships among shape semantics are discovered.

Learning the situatedness of design knowledge within which it was recognised provides potential advantages to guide its use when similar situations arise. This is achieved through developing multiple representations of a design composition; recognising shape semantics at each representation; and learning the regularities of relationships among shape semantics across various representations within which they were recognised. Within each learned regularity, if a single shape semantic is chosen to be the knowledge in focus, then the remaining shape semantics within this regularity construct its situatedness within which it was recognised.

The remainder of this paper develops and describes multiple representations as a platform for situated learning systems in designing. Section 2 addresses the notion of situatedness of knowledge and Section 3 introduces situatedness in designing. Multiple representations in designing is introduced in Section 4, while Section 5 introduces the recognition of shape semantics from the representations. Section 6 introduces how these representations can serve as a platform for situated learning systems in designing.

2. Situatedness of knowledge

There are several definitions of what is the “situation”. The conception of situation we will use here is similar to Heidegger’s [3,4]. Heidegger [4] defines the situation as “the architect’s context including the physical surroundings, the available tools, and the circumstances surrounding the task at hand within the architect’s personal and professional aim”. The physical surroundings of visual objects help to distinguish the situatedness of certain objects in focus by relating it to the surrounding within which it is placed. An illustration of this notion is shown in Fig. 1 [5]. Consider the image in Fig. 1(b), when read, it is “THE CAT”; yet upon close inspection, the H in THE is the same figure as the A in the CAT. If the figures of H/A were presented in isolation as in Fig. 1(a), out of context, we would be confused as to their correct identity. The physical surroundings provided by adjacent letters and our knowledge of the language help to determine the identification of each letter based upon its surroundings that create the situation. Thus, the situation is the immediate context in conjunction with the knowledge in focus within which it was recognised.

The situation constitutes a network of significance in terms of which parts of the surroundings are in conjunction with the knowledge in focus. That is, if something becomes the knowledge in focus, then its relation to the rest of the surroundings identifies its situation. So the knowledge must be seen with respect to the possible situations potentially associated with it. The situation for the knowledge in focus is constructed through finding the regularities of relationships within the surroundings in terms of which parts of those surroundings are in conjunction with it through a number of contexts at a particular moment of time. This situated view associates knowledge in focus to situations in the environment within which they occurred. Whenever moving within different surroundings, there is the possibility for these associations to be refined and to lead to modifying previously constructed situations or creating new ones. So, the situation cannot be completely determined in advance or given a priori like something objectively present waiting to be selected. Standard artificial intelligence (AI) systems often operate in a way that does not adequately consider the change of situatedness in response to the changes in the environment over time [6].

3. Situatedness in designing

Designing has been looked upon as not only problem solving but also a continual problem finding [7–12]. For Schön [12] designing is not primarily a form of problem solving, information processing, or searching, but is a “conversation with the materials of a situation”. Whenever a designer makes things, he uses particular materials and employs a distinctive medium and language. During the design process designers tend to produce consequences other than those intended. When this happens, the designers may take account of the unintended changes they have made. This paper views designing, not as an anticipative act rather as a situated activity [13]. Situated means that the result of designing is not based on actions of what is being designed or independent of when, where and how it has been designed. Designers’ actions are situation dependent as to what they have designed. The situatedness in

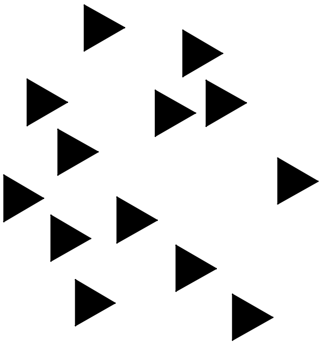


Fig. 2. An example of multiple views of the same composition: look at the display of triangles, in which directions do they point? Can you make the direction change? [5].

designing is concerned with locating design knowledge in relation to its situation. The primary distinction of this approach is that since designing can be viewed as ill-defined problem solving, the situatedness of design knowledge cannot be completely predefined but rather constructed on the fly based on need.

3.1. Why bother about situatedness in learning in designing?

A long held view in AI in design is that designing can be modelled as search within a given representation of the world. Designing has recently been modelled as a form of exploration, where the world that is to be searched has first to be constructed and located. Both of these views are founded on the notion that knowledge exists outside of its use and only has to be applied to be useful. Thus, learning in designing is largely concerned with finding relationships between structure and behaviour independent of its locus and application and representing that as knowledge which then can be applied later. Situatedness is needed to augment these models of the design process. Situatedness holds that [14] “where you are when you do what you do matters”. What a designer has done up to this point affects his response to a given designing situation [15]. Attention to the situation entails taking the whole designing environment in which the knowledge in focus has been recognised into account. This is not to be confused with situation modelling. Modelling a situation would imply having to define how the situation is perceived and how the environment is interpreted.

Situated acts such as conceptual designing are different to the mere application of knowledge. Situated acts require that the situation itself is constructed and as a consequence what is knowledge and what is situation is constructed on the fly based on need rather than based on previously defined knowledge. The effect of this is that the state space within which a designer is operating is potentially constantly changing as the designer constructs worlds of interest [16]. Representations and consequent situations are not preset but are produced at the time a need arises. Hence, knowledge is only useful in specific situations [17]. Thus, the utility of knowledge is determined by its situatedness not by any absolute measure. Situated learning in designing here is concerned with finding the regularities of relationships between the design knowledge and the situations within which it was recognised.

4. Multiple representations in designing

Since designing typically occurs within certain circumstances where it is not possible or feasible to manipulate the world directly, designers manipulate representations of the world [18]. Representations encompass a wide range of possible ways to store information about an object; its function, behaviour and structure. Representations may include objects and relationships, which establish links from one object to others. Moreover, the representations may influence the result obtained since each representation is usually associated with a range of desired applications and is a partial view of the object it represents [19]. This partial view is an interpretation of the object often aimed at a particular application or purpose. There is no one representation that allows detailed consideration of all possible concerns and permits any arbitrary type of description. One way to represent such diversity is through the use of multiple representations. So it is often convenient and sometimes necessary to use a number of different representations. Equally important in support of multiple representations is that some specific representations favour specific outcomes and since it is not known in advance which outcomes may be required so it is not known a priori which representation to use [20]. During conceptual designing, multiple representations provide opportunities for designers to conceptualise their designs differently. Using multiple representations is one way to allow for different interpretations of what has been designed. Multiple representations allow for the coexistence of several descriptions of the same entity [21]. They are commonly called perspectives in knowledge representation languages, views in the database world and representations in the designing world. Landau [22] suggested that objects could be represented in terms of very different geometric descriptions or shape structures to perform different purposes. For example, a square can be represented as a set of four points; a set of four lines segments; a set of four infinite lines; and the perimeter of a given area or a region defined by four half planes. Different relationships might appear from these different representations. Multiple representations can be viewed as a result of multiple seeing through the concept of seeing, moving and seeing [23]. For instance, top down processing affects the way we see geometric features of shapes as in the case of Fig. 2. For many people the triangles seem to point to the right, but if we try to orient them so they point upward and slightly left, we can do this with ease; or we can make the triangles point downward and left.

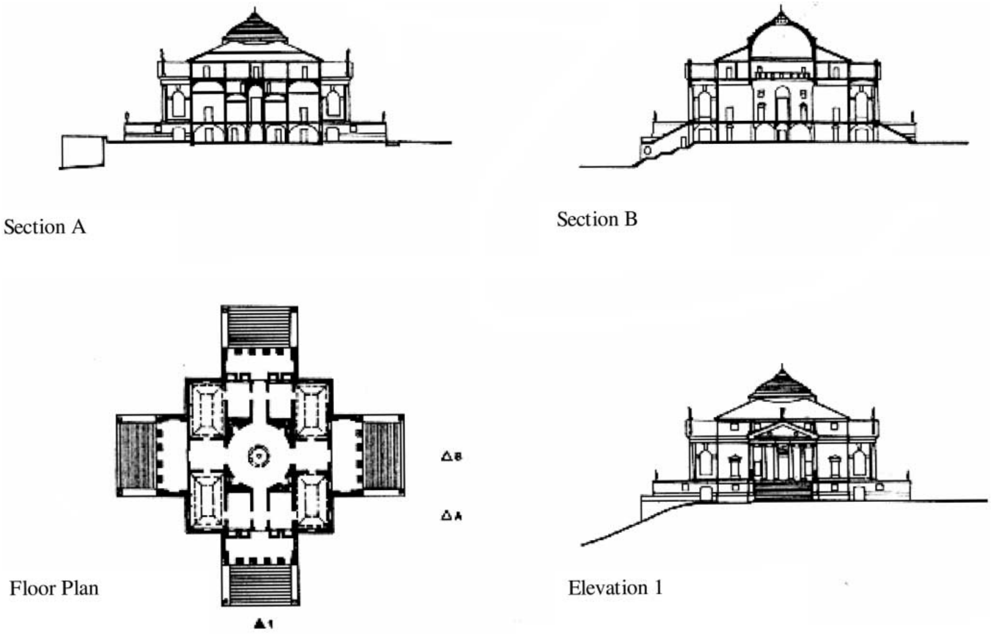


Fig. 3. Descriptions of the design composition of Villa Capra, Vicenza, Italy [24].

4.1. Why use multiple representations for situated learning in designing?

What makes multiple representations interesting in the context of situatedness is that they provide the opportunity for different and rich relationships to be captured from what looks to be a single design composition. This allows a learning system to move through a number of representations, or states of situatedness, in which the system can distinguish the situatedness of the knowledge in focus as it is being acquired. Within the domain of architectural design composition, during designing a designer might encounter many different situations at various stages to reach the final product. Consequently, different representations of the design composition might have been developed during this process. Fig. 3 illustrates descriptions of an architectural design composition: floor plan, elevation and sections of Villa Capra, Italy [24]. Different representations that may have been interpreted and developed by the designer at different stages in the designing of Villa Capra are illustrated in Fig. 4. In these representations, relationships assume a central role. For example, in architectural floor plans, the individual components are usually not as interesting as the relationships among them. Multiple representations through re-representing designs from different views provide a platform to learn the relationships among different design knowledge across the representations. The regularities of these relationships construct the situatedness of the design knowledge and have the potential to guide its use when similar situations arise. In other words, multiple representations provide a platform for the learning system to capture the situatedness of design knowledge.

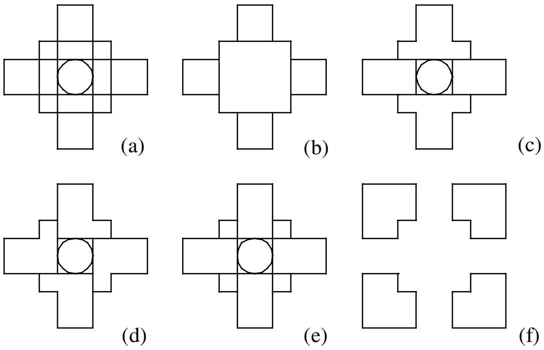


Fig. 4. Some of possible representations that might be interpreted by the designer during different design stages: (a) lines; (b) blocks; (c) components reflected; (d) components rotated; (e) centrality; and (f) background/foreground.

5. Recognition of shape semantics from multiple representations

We will use the domain of shape composition as a vehicle to demonstrate the notion of situatedness in designing and learning, however the underlying conceptual approach is applicable in other domains. In architectural designing, as in many other disciplines, shape composition is an important designing activity. Through shape composition, designers express ideas, concepts and construct situations. The formation and discovery of relationships among shape parts of a design composition are fundamental tasks in designing [25,26]. Shapes are the way we begin to understand the visual world our visual sense brings to us [27]. While seeing a representation of a design composition, various shape semantics can be recognised by designers.

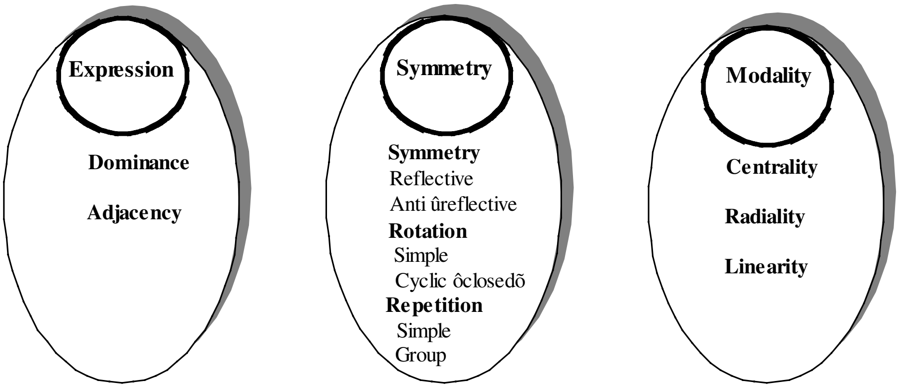


Fig. 5. Selected shape semantics of architectural shape composition.

They discover various shape semantics related to their interest. A shape semantic is a set of characteristics with a semantic meaning based on a particular view of the shapes. Shape semantics and relationships among them may play a crucial role in developing further design concepts. Various types of shape semantics can be explained in a variety of ways by grouping structures using the laws of figure perception [28]. Grouping structures is supported by such factors as: repetition, similarity, proximity, symmetry and orientation. Repetition of aligned elements, where all the elements are similar or congruent, plays an important role in grouping. Gestalt theory deals with the grouping phenomenon in a comprehensive way. The central concept of that theory is the concept of Gestalt-form or configuration of any segregated whole or unit [29].

There are many types of architectural shape semantics that can be recognised from the representations of a design composition. In this work, we selected three types of shape semantics of architectural shape composition: expression, symmetry and modality as shown in Fig. 5. The reason for this selection is that they are amongst the most prominent semantics in architectural shape composition. These shape semantics are concerned with the visual relationships between the parts in a design composition. Expression indicates the impression of a feature or a defined assemblage of features such as dominance. Visual dominance reflects the effect of shape size and spatial location. Symmetry indicates harmony and conformity among the parts such as repetition and reflective symmetry. Modality shows the characteristics of how the parts of the design composition are put together such as centrality and linearity.

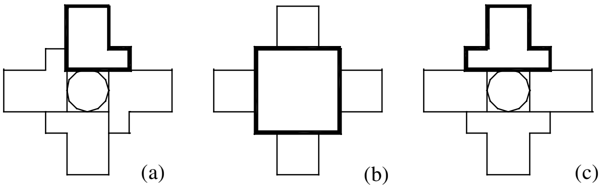


Fig. 6. Recognition of different shape semantics from multiple representations of design composition: (a) rotation; (b) centrality; and (c) reflection.

Multiple representations allow and provide the opportunity for a wide range of interpretations of the design composition [30] whereby each interpretation reveals certain shape semantics. Hence, multiple representations may allow implicit shape semantics in one representation to become explicit in another representation. This enriches the opportunity for a system to recognise various semantics from different representations. For instance, in the representations shown in Fig. 4 the shape semantics: rotation and reflective symmetry are readily recognised only at the representations shown in Fig. 6(a) and (c), respectively. Other shape semantics, such as dominance, are not easily recognised using these representations where it could be readily recognised in another representation such as that shown in Fig. 6(b).

6. Situated learning from multiple representations

Situated learning about shape semantics is not merely recognising the shape semantics from the representation of a deign composition rather it is learning the regularities of relationships among these shape semantics across various representations. These relationships enrich the shape semantics by relating them to their situations and indicate their applicability conditions if they are to be used later in similar situations. Learning the regularities of relationships among shape semantics across the representations is the key for a system to construct the situatedness of these shape semantics. These relationships are not predetermined but constructed while learning based on what is recognised from each representation. Since the development of representations is an ongoing process while designing, the design space is not fixed rather it is extended. This view is not accommodated in Simon's view [11] of designing where the design space is defined a priori.

All shape semantics within each regularity are candidates for both knowledge and situation. Thus, within each learned regularity of relationships, if a single shape semantic is chosen to be the knowledge in focus then the remaining shape semantics within this regularity become candidates for that knowledge's situation. Multiple representations

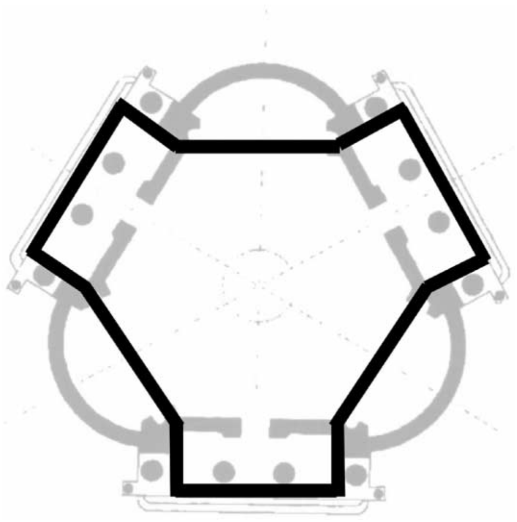


Fig. 7. The outline of the entries and the hexagon hall of the Sepulchral Church are selected as a base representation of the design composition, Sir John Soane, 1796 [after 34].

provide a medium to learn the situatedness of shape semantics whereby in each representation there is the possibility to reinforce what is the situation for each shape semantic. Since it is not known at the time of learning which is useful knowledge and what is therefore the situation all regularities need to be treated as potentially useful knowledge. The processes of learning the situatedness of shape semantics from multiple representations cover the following:

1. Initial representation: the initial visual representation of the design composition;
2. Multiple representations: development of different representations of the same design composition;
3. Shape semantics recognition: recognising shape semantics that are readily recognisable at each representation; and
4. Situated learning: finding the regularities of relationships among shape semantics in relation to their situations within which they were recognised.

Here we will restrict ourselves to multiple representations of a single shape and use those representations as the base from which situated learning occurs. We do so without loss of generality in terms of multiple representations of a variety of shapes or more generally objects.

6.1. Initial representation of a design composition

In this work, segments in infinite maximal lines are used as representational primitives to construct a symbolic representation as the initial representation of the shapes in a design composition to support shape recognition. A line segment in a shape is maximal whenever no other line segment in the shape contains it. An extended maximal line is a line segment within which at least one maximal line is embedded. An infinite maximal line is the infinite line in which an extended maximal line is embedded. There are three kinds of properties of interest of infinite maximal lines: topological properties, geometrical properties and dimensional properties. Gero and Yan [31] have developed the notion of infinite maximal lines for representing a shape. This symbolic representation has been successfully implemented for discovering emergent shapes in two- and three-dimensional domains [32,33]. We choose as an example of a design composition, the outlines of the entries and the hexagon hall of the Sepulchral Church, Sir John Soane 1796, [34] as shown in Fig. 7. Using infinite maximal lines as representational primitives, the general form of the symbolic representation of the design composition's shape is:

$$\mathbf{S}_i = \{\mathbf{N}_l; [\mathbf{i}_{jk}]\}$$

where $\mathbf{N}_l$ is the number of infinite maximal lines constituting a shape $\mathbf{S}_i$ and $[\mathbf{i}_{jk}]$ is the description of the intersections of infinite maximal lines defining that shape. An alternative form is:

$$\mathbf{S}_i = \{\mathbf{N}_l; [\boldsymbol{l}_i]\}$$

where $[\boldsymbol{l}_i]$ is the description of the infinite maximal lines defining that shape. The symbolic representations of the initial representation shown in Fig. 8 are as follows:

$$\mathbf{S}_i = \{\mathbf{N}_l; [\mathbf{i}_{jk}]\}$$

$$\mathbf{S}_1 = \{12;\ [i_{ab,}i_{bc,}i_{cd,}i_{de,}i_{ef,}i_{fg,}i_{gh,}i_{hj,}i_{jk,}i_{km,}i_{mn,}i_{na}]\}$$

$$\mathbf{S}_i = \{\mathbf{N}_l; [\boldsymbol{l}_i]\}$$

$$\begin{aligned}\mathbf{S}_1 = \{12;[&l_a, l_b, l_c, l_d, l_e, l_f, l_g, l_h, l_j, l_k, l_m, l_n],\\ &l_a \parallel l_g, l_b \parallel l_n, l_c \parallel l_j, l_d \parallel l_f, l_e \parallel l_m, l_h \parallel l_k,\\ &l_n \perp l_a, l_a \perp l_b, l_d \perp l_e, l_e \perp l_f, l_h \perp l_j, l_j \perp l_k,\\ &A(l_m, l_n) = A(l_b, l_c) = A(l_c, l_d)\\ &\quad = A(l_f, l_g) = A(l_g, l_h) = A(l_k, l_m),\\ &d(i_{na}, i_{ab}) = d(i_{de}, i_{ef}) = d(i_{hj}, i_{jk}), d(i_{ab}, i_{bc})\\ &\quad = d(i_{cd}, i_{de}) = d(i_{ef}, i_{fg}) = d(i_{gh}, i_{hjj}) = d(i_{jk}, i_{km})\\ &\quad = d(i_{mn}, i_{na}), d(i_{bc}, i_{cd}) = d(i_{fg}, i_{gh}) = d(i_{km}, i_{mn})\}\end{aligned}$$

where A is the angle between two line segments; d, the distance or length between two intersections of maximal lines; i_{jk}, the intersection of two maximal lines; l_j and l_k; $\parallel$, the lines are parallel; and $\perp$, the lines are perpendicular

6.2. Development of multiple representations

The processes of developing multiple representations, as shown in Fig. 9, commence with representing the initial

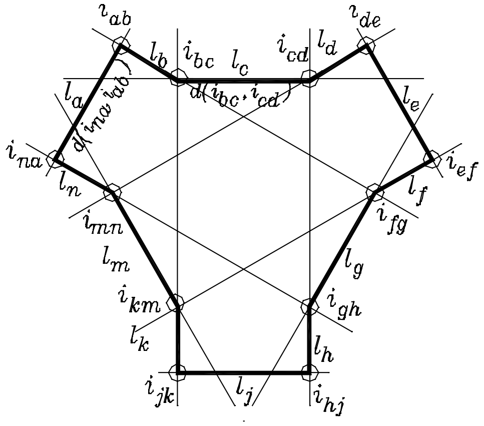


Fig. 8. Infinite maximal lines of the initial design composition.

representation of the shape of the design composition as infinite maximal lines. Generating multiple representations can be through decomposing the initial representation into its components and grouping the decomposed objects based upon the congruency of their structural properties. The decomposition of the initial representation can be either for the boundary of the shape or for the areas within the shape. The first leads to unbounded *n*-sided shapes and the latter results in bounded *n*-sided shapes where emergent shapes appear as shown in Sections 6.2.1 to 6.2.4. In this process new shapes that were implicit in the initial representation may become explicit in the changed representations. This has been defined as one form of visual emergence [35,36]. One way for visual emergence to occur is through alternative groupings of the shapes produced through the intersections of infinite maximal lines of the line segments in the initial representation as shown in Sections 6.2.4 to 6.2.6. In this paper we have developed 32 representations of the exemplar design composition. Some of them are presented graphically in the following sections. Their symbolic representations in a concise syntax are presented in Table 1. The remainder of this section presents the development of some of the multiple representations.

6.2.1. Unbounded one-sided subshapes

An unbounded one-sided subshape is a shape consisting of one line segment that does not form a closed shape. The similarity among unbounded one-sided subshapes is one way of grouping the structural elements in the initial representation. The similarity measurements are the distance between the intersections of each two maximal lines, and distances from the centre of that maximal line and the centre of the whole shape. A labelling for line segments based on this kind of similarity is illustrated in Fig. 10 and the description of its symbolic representation is:

$$\mathbf{S}_1 = \{12; [l_a, l_b, l_c, l_d, l_e, l_f, l_g, l_h, l_j, l_k, l_m, l_n]\}$$

$$\mathbf{S}_1 = \{12; [x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2]\}$$

$$\mathbf{R}_1 :: \mathbf{S}_1 = \{(4x_1, 4x_2, 4x_3)\}$$

where the lengths of line segments embedded in l_a, l_e and l_j are equal, so they are labelled as x_1. Similarly with l_b, l_d, l_f, l_h, l_k and l_n are labelled as x_2 and l_o, l_g and l_m are labelled as x_3. The following notations are used in the syntax of representations: $\mathbf{R}_i :: \mathbf{S}_j$ is the re-representation number i for the initial representation of the shape $\mathbf{S}_j$, "( )" indicates that line segments are unbounded and "[ ]" indicates that line

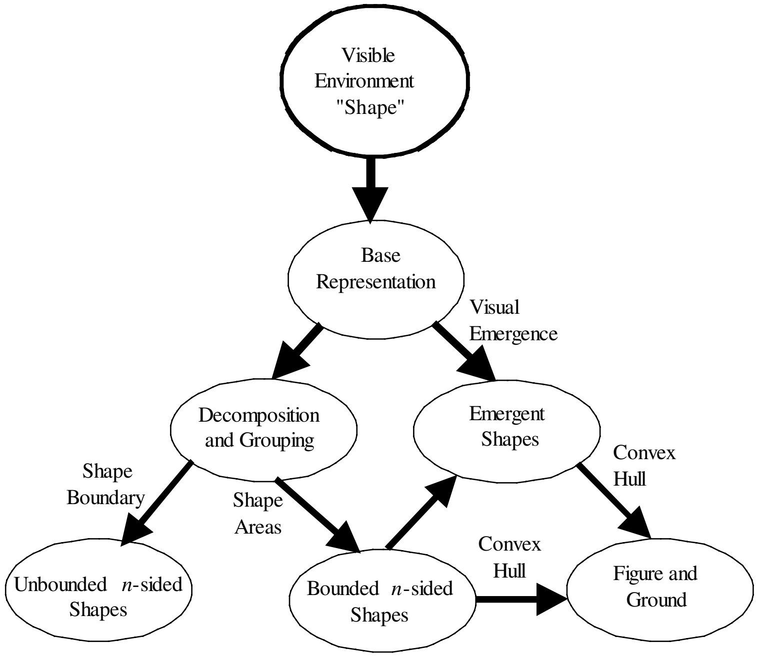


Fig. 9. The process of developing multiple representations.

Table 1
A set of 32 developed representations of the design composition shown in Fig. 7 and the group of shape semantics recognised at each representation

No.	Multiple representations		Recognised shape semantics at each representation
	Label	Concise syntax	
R_1	Unbounded one-sided subshapes	$\mathbf{S}_1 = \{12; [x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2]\}$	$\mathbf{P}_l\ (x_1, x_2, x_3);$
		$\mathbf{S}_1 = \{3x_1, 6x_2, 3x_3\}$	$\mathbf{P}_r\ (x_1, x_2, x_3)$
R_2	Unbounded two-sided subshapes	$\mathbf{S}_1 = \{[3((x_1, x_2), (x_3, x_2))]\}$	$\mathbf{R}_c\ ((x_1, x_2), (x_3, x_2))$
R_3		$\mathbf{S}_1 = \{[3((x_2, x_3), (x_2, x_1))]\}$	$\mathbf{R}_c\ ((x_2, x_3), (x_2, x_1))$
R_4	Unbounded three-sided subshapes	$\mathbf{S}_1 = \{[3((x_1, x_2, x_3), (x_2))]\}$	$\mathbf{R}_n\ ((x_1, x_2, x_3)\ (x_2))$
R_5		$\mathbf{S}_1 = \{[3((x_3, x_2, x_1), (x_2))]\}$	$\mathbf{R}_n\ ((x_3, x_2, x_1)\ (x_2))$
R_6		$\mathbf{S}_1 = \{[3((x_1), (x_2, x_3, x_2))]\}$	$\mathbf{P}_p\ x_2 \mid (x_2, x_3, x_2)$; $\mathbf{R}_n\ ((x_2, x_3, x_2), x_2)$; $\mathbf{S}_t\ (x_2, x_3, x_2)$
R_7		$\mathbf{S}_1 = \{[3((x_2, x_1, x_2), (x_3))]\}$	$\mathbf{P}_p\ x_3 \mid (x_2, x_1, x_2)$; $\mathbf{R}_n\ ((x_2, x_1, x_2), x_2)$; $\mathbf{S}_t\ (x_2, x_3, x_2)$
R_8	Unbounded four-sided subshapes	$\mathbf{S}_1 = \{[3(x_1, x_2, x_3, x_2)]\}$	$\mathbf{R}_c\ (x_1, x_2, x_3, x_2)$; $\mathbf{P}_p\ x_2 \mid (x_1, x_2, x_3, x_2)$; $\mathbf{S}_t\ (x_1, x_2, x_3, x_2)$
R_9		$\mathbf{S}_1 = \{[3(x_2, x_3, x_2, x_1)]\}$	As above
R_{10}		$\mathbf{S}_1 = \{[3(x_3, x_2, x_1, x_2)]\}$	As above
R_{11}		$\mathbf{S}_1 = \{[3(x_2, x_1, x_2, x_3)]\}$	As above
R_{12}	Unbounded five-sided subshapes	$\mathbf{S}_1 = \{[(x_1, x_2, x_3, x_2, x_1), (x_2, x_3, x_2), x_1, (x_2, x_3, x_2)]\}$	$\mathbf{P}_n\ (x_2, x_3, x_2) \mid (x_1, x_2, x_3, x_2, x_1)$; $\mathbf{S}_r\ (x_2, x_3, x_2) \mid (x_1, x_2, x_3, x_2, x_1)$
R_{13}		$\mathbf{S}_1 = \{[(x_1, x_2, x_3, x_2, x_1, x_2), x_3, (x_2, x_1, x_2, x_3, x_2,)]\}$	$\mathbf{P}_p\ (x_2, x_3, x_2, x_1, x_2)$; $\mathbf{S}_r\ (x_2, x_3, x_2, x_1, x_2)$
R_{14}		$\mathbf{S}_1 = \{[(x_2, x_1, x_2), (x_3, x_2, x_1, x_2, x_3), (x_2, x_1, x_2), x_3]\}$	$\mathbf{P}_p\ (x_2, x_1, x_2)$; $\mathbf{S}_r\ (x_2, x_1, x_2)$; $\mathbf{R}_s\ (x_2, x_1, x_2)$
R_{15}		$\mathbf{S}_1 = \{[(x_1, x_2), (x_3, x_2, x_1, x_2, x_3), (x_2, x_1), (x_2, x_3, x_2)]\}$	$\mathbf{P}_p\ (x_1, x_2)$; $\mathbf{S}_r\ (x_1, x_2)$
R_{16}		$\mathbf{S}_1 = \{[(x_2, x_3, x_2, x_1, x_2), x_3, (x_2, x_1, x_2, x_3, x_2), x_1]\}$	$\mathbf{P}_p\ (x_2, x_3, x_2, x_1, x_2)$; $\mathbf{S}_r\ (x_2, x_3, x_2, x_1, x_2)$
R_{17}		$\mathbf{S}_1 = \{[(x_1, x_2, x_3), (x_2, x_1, x_2, x_3, x_2), (x_1, x_2, x_3), x_2]\}$	$\mathbf{P}_p\ (x_1, x_2, x_3)$; $\mathbf{R}_s\ (x_1, x_2, x_3)$
R_{18}		$\mathbf{S}_1 = \{[(x_1, x_2), x_3, (x_2, x_1, x_2, x_3, x_2), (x_1, x_2), x_3, x_2]\}$	$\mathbf{P}_p\ (x_1, x_2,)$; $\mathbf{S}_r\ (x_1, x_2)$
R_{19}		$\mathbf{S}_1 = \{[x_1, (x_2, x_3), (x_2, x_1, x_2, x_3, x_2), x_1, (x_2, x_3), x_2]\}$	$\mathbf{P}_p\ (x_2, x_3)$; $\mathbf{S}_r\ (x_2, x_3)$
R_{20}	Bounded four-sided subshapes	$\mathbf{S}_1 = \{3[S_2], 2[S_3]\}$	$\mathbf{S}_r\ [S_3]$; $\mathbf{R}_s\ [S_2]$
R_{21}		$\mathbf{S}_1 = \{3[S_2], [S_4]\}$	$\mathbf{S}_r\ [S_2]$; $\mathbf{R}_s\ [S_2]$; $\mathbf{D}_m\ [S_4]$
R_{22}	Bounded four-sided shapes & three-sided subshapes	$\mathbf{S}_1 = \{3[S_2], 2[S_5], 2[S_6]\}$	$\mathbf{S}_r\ ([S_2]\ [S_5])$; $\mathbf{R}_s\ [S_2]$; $\mathbf{S}_n\ [S_6]$
R_{23}		$\mathbf{S}_1 = \{3[S_2], 2[S_6], 2[S_7]\}$	$\mathbf{S}_r\ [S_2]$; $\mathbf{R}_s\ [S_2]$; $\mathbf{S}_r\ ([S_5]\ [S_6])$
R_{24}	Figure and ground perception	$\mathbf{S}_1 = \{[S_1], 3[S_{13}]\}$	$\mathbf{S}_r\ [S_{13}]$; $\mathbf{R}_s\ [S_1]$; $\mathbf{T}_r\ [S_1]$; $\mathbf{C}_e\ [S_1]$
R_{25}		$S_1 = \{[S_1], 3[S_{12}]\}$	$\mathbf{S}_r\ [S_{12}]$; $\mathbf{R}_s\ [S_{12}]$; $\mathbf{T}_r\ [S_1]$; $\mathbf{C}_e\ [S_1]$
R_{26}	Emergent shapes	$S_1 = \{3[S_{14}], 3[S_{15}], [S_{16}]\}$	$\mathbf{S}_r\ [S_{14}]$; $\mathbf{R}_s\ [S_{14}]$; $\mathbf{C}_e\ [S_{16}]$; $\mathbf{R}_c\ [S_{15}]$
R_{27}		$\mathbf{S}_1 = \{3[S_{14}], 3[S_{18}], 6[S_{17}], [S_{16}]\}$	$\mathbf{S}_r\ [S_{14}][S_{18}]$; $R_s[S_{14}]$; $\mathbf{C}_e\ [S_{16}]$; $\mathbf{R}_c[S_{17}]$
R_{28}		$\mathbf{S}_1 = \{3[S_{14}], 3[S_{18}], [S_{19}]\}$	$\mathbf{S}_r\ ([S_{14}]\ [S_{18}])$; $\mathbf{C}_e\ [S_{19}]$; $\mathbf{D}_m\ [S_{19}]$
R_{29}		$\mathbf{S}_1 = \{3[S_{14}], [S_{20}]\}$	$\mathbf{S}_r\ ([S_{14}]\ [S_{18}])$; $\mathbf{R}_s\ [S_{14}]$; $\mathbf{C}_e\ [S_{20}]$; $\mathbf{D}_m\ [S_{20}]$
R_{30}		$\mathbf{S}_1 = \{3[S_{21}], 3[S_{18}], [S_{16}]\}$	$\mathbf{S}_r\ ([S_{18}]\ [S_{21}])$; $R_s\ [S_{18}]$; $\mathbf{C}_e\ [S_{16}]$; $\mathbf{D}_m\ [S_{16}]$; $\mathbf{R}_c[S_{21}]$
R_{31}		$\mathbf{S}_1 = \{[S_{22}], 3[S_{18}]\}$	$\mathbf{S}_r\ [S_{18}]$; $\mathbf{R}_s\ [S_{18}]$; $\mathbf{C}_e\ [S_{22}]$; $\mathbf{D}_m\ [S_{22}]$
R_{32}		$\mathbf{S}_1 = \{6[S_{23}], [S_{24}]\}$	$\mathbf{S}_r\ [S_{23}]$; $\mathbf{R}_s[S_{23}]$; $\mathbf{C}_e\ [S_{24}]$; $\mathbf{D}_m\ [S_{24}]$

segments are bounded which means a number of connected line segments jointly form a closed circuit.

6.2.2. Unbounded two-sided subshapes

In unbounded two-sided subshapes the similarity measurements are the repetitions of two contiguous line segments, distance between the intersection of each two maximal lines, distance from the centre of that maximal line and the centre of the whole shape. Thus, two representations, $\mathbf{R}_1$ and $\mathbf{R}_2$, developed from the initial representation are shown in Fig. 11(a) and (b) and the descriptions of their symbolic representations are:

$$\mathbf{S}_1 = \{[x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2]\}$$

$$\mathbf{R}_2 :: \mathbf{S}_1 = \{[3((x_1, x_2), (x_3, x_2))]\}$$

$$\mathbf{R}_3 :: \mathbf{S}_1 = \{[3((x_2, x_3), (x_2, x_1))]\}.$$

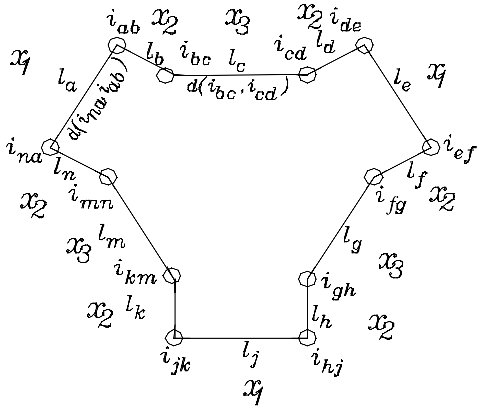


Fig. 10. Labelling line segments with x_1, x_2 and x_3 based on similarity measurements.

6.2.3. Unbounded three-sided subshapes

The same similarity measures used in Section 6.2.2 are applied but with three contiguous line segments. Four representations $\mathbf{R}_4$, $\mathbf{R}_5$, $\mathbf{R}_6$ and $\mathbf{R}_7$ of unbounded three-sided subshapes are developed as shown in 12(a)–(d) and the descriptions of their symbolic representations are:

$$\mathbf{S}_1 = \{[x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2]\}$$

$$\mathbf{R}_4 :: \mathbf{S}_1 = \{[3((x_1, x_2, x_3), (x_2))]\}$$

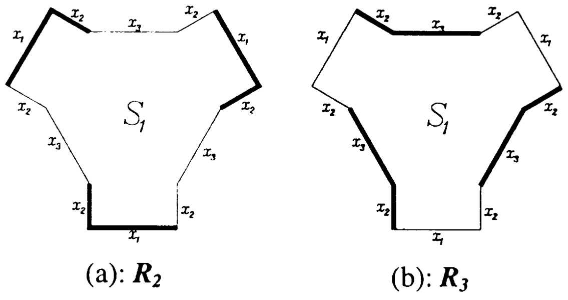
$$\mathbf{R}_5 :: \mathbf{S}_1 = \{[3((x_3, x_2, x_1), (x_2))]\}$$

$$\mathbf{R}_6 :: \mathbf{S}_1 = \{[3((x_1), (x_2, x_3, x_2))]\}$$

$$\mathbf{R}_7 :: \mathbf{S}_1 = \{[3((x_2, x_1, x_2), (x_3))]\}.$$

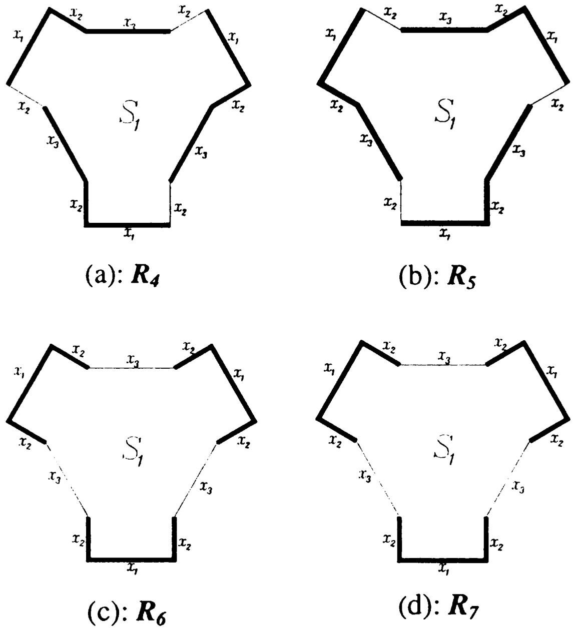
6.2.4. Bounded n-sided subshapes

Bounded *n*-sided subshapes are generated through decomposing the initial representation to areas or subshapes within the boundary of the initial shape. The initial shape can be decomposed through connecting the nodes of the shape alternatively to a mixture of different or equal *n*-sided bounded subshapes. The concept of re-representing the shape adopted in this work includes changing the structural knowledge in the initial representation in which some structural elements embedded in the representation were only implicit. As a result, new subshapes that exist only implicitly in the shape and never explicitly indicated are emerged. Examples of bounded four-sided subshapes, emergent shapes, consisting of various numbers of line segments joined together to form closed shapes are $[x_2,x_1,x_2,x_1]$ labelled as $[\mathbf{S}_2]$ and $[x_3,x_1,x_4,x_1]$ labelled as $[\mathbf{S}_3]$ as shown in Fig. 13. In this representation and onwards, different labels of other line segments such as x_4 have been introduced. This is because both the length embedded in its line segments and the distance from its centre to the centre of the whole shape are not equal to any of these line segments used before. The subshapes are grouped based on their congruency to form different representations of the initial representation. For instance, the symbolic description of one of the bounded four-sided representations, $\mathbf{R}_{20}$, shown in Fig. 13 is:



(a): ***R*₂** (b): ***R*₃**

Fig. 11. Two developed representations of unbounded two-sided subshapes: (a) and (b) show $\mathbf{R}_2$ and $\mathbf{R}_3$.



(a): ***R*₄** (b): ***R*₅** (c): ***R*₆** (d): ***R*₇**

Fig. 12. Four developed representations of unbounded three-sided subshapes: (a)–(d) show $\mathbf{R}_4$ to $\mathbf{R}_7$, respectively.

$$\mathbf{S}_1 = \{12; [i_{ab}, i_{bc}, i_{cd}, i_{de}, i_{ef}, i_{fg}, i_{gh}, i_{hj}, i_{jk}, i_{km}, i_{mn}, i_{na}]\}$$

$$\mathbf{S}_1 = \{[i_{mn}, i_{na}, i_{ab}, i_{bc}], [i_{cd}, i_{de}, i_{ef}, i_{fg}], [i_{gh}, i_{hj}, i_{jk}, i_{km}], [i_{bc}, i_{cd}, i_{fg}, i_{mn}], [i_{gh}, i_{km}, i_{mn}, i_{fg}]\}$$

$$\mathbf{S}_1 = \{[x_2, x_1, x_2, x_1], [x_2, x_1, x_2, x_1], [x_2, x_1, x_2, x_1], [x_3, x_1, x_4, x_1], [x_3, x_1, x_3, x_4]\}$$

$$\mathbf{S}_1 = \{[S_2], [S_2], [S_2], [S_3], [S_3]\}$$

$$\mathbf{R}_{20} :: \mathbf{S}_1 = \{3[S_2], 2[S_3]\}.$$

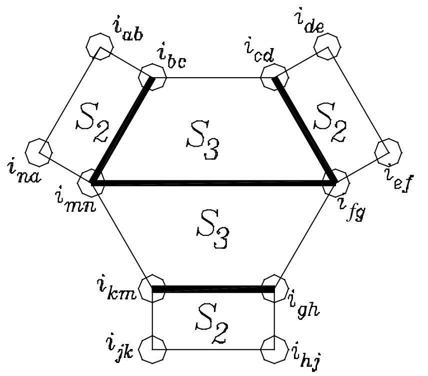


Fig. 13. An example of bounded four-sided subshapes representation $\mathbf{R}_{20}$.

6.2.5. Figure and ground

The figure and ground perception hypothesis developed in Gestalt psychology helps to explore other aspects of how our visual system functions [37]. It seems that our visual system simplifies the visual scene into a figure that we look at and a ground that is everything else in the scene, which forms the background. For instance, the shape shown in Fig. 14(a) could be seen as a vase. The construction of the new representation of that shape is through creating either a standard convex hull or an outermost convex hull. After constructing the new representation as shown in Fig. 14(b) and (c) [37], the shape could be seen either as a white central vase, or as a pair of black faces in profile that are looking towards each other. Generally when we see one of these perceptions, the other region forms a background and is not seen so to see both percepts requires switching back and forth. The contour dividing the black and white regions of the picture appears to belong to whichever region is perceived as the figure. Figure and ground perception is a way to represent the illusory shapes as might be conceived by human. Two ways to develop representations under which the figure and ground perception can be introduced are through the standard convex hull or through the outermost convex hull of the initial representation. The outermost convex hull can be constructed by joining the farthest intersections of infinite maximal lines that represent the shape, shown in Fig. 15(a), as shown in Fig. 15(b) and (c). The standard convex hull can be constructed simply by joining the nodes of the shape, shown in Fig. 16(a), at the outline contour as shown in Fig. 16(b) and (c). The description of the symbolic representations for both $\mathbf{R}_{24}$ and $\mathbf{R}_{25}$ are, where $\mathbf{S}_\mathrm{o}$ and $\mathbf{S}_\mathrm{t}$ refer to the new constructed shapes from outermost and standard convex hull respectively:

$$\mathbf{S}_\mathrm{o} = \{[i_{mn}, i_{na}, i_{ab}, i_{bc}, i_{cd}, i_{de}, i_{ef}, i_{fg}, i_{gh}, i_{hj}, i_{jk}, i_{km}],$$
$$[i_{na}, i_{bc}, i_{cd}, i_{de}, i_{ae}], [i_{ef}, i_{fg}, i_{gh}, i_{hj}, i_{ej}], [i_{jk}, i_{km}, i_{mn}, i_{na}, i_{ja}]\}$$

$$\mathbf{S}_\mathrm{o} = \{[x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2],$$
$$[x_2, x_3, x_2, x_{10}, x_{10}], [x_2, x_3, x_2, x_{10}, x_{10}], [x_2, x_3, x_2, x_{10}, x_{10}]\}$$

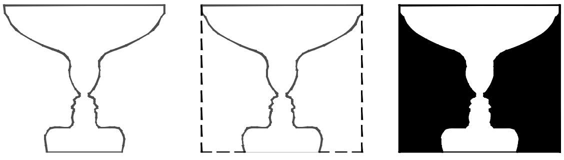

(a) (b) (c)

Fig. 14. Figure and ground perception, after [36].

$$\mathbf{S}_\mathrm{o} = \{[S_1], [S_{13}], [S_{13}], [S_{13}]\}$$

$$\mathbf{R}_{24} :: \mathbf{S}_\mathrm{o} = \{[S_1], 3[S_{13}]\}$$

$$\mathbf{S}_\mathrm{t} = \{[i_{mn}, i_{na}, i_{ab}, i_{bc}, i_{cd}, i_{de}, i_{ef}, i_{fg}, i_{gh}, i_{hj}, i_{jk}, i_{km}],$$
$$[i_{na}, i_{bc}, i_{cd}, i_{de}], [i_{ef}, i_{fg}, i_{gh}, i_{hj}], [i_{jk}, i_{km}, i_{mn}, i_{na}]\}$$

$$\mathbf{S}_\mathrm{t} = \{[x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2, x_1, x_2, x_3, x_2],$$
$$[x_2, x_3, x_2, x_9], [x_2, x_3, x_2, x_9], [x_2, x_3, x_2, x_9]\}$$

$$\mathbf{S}_\mathrm{t} = \{[S_1], [S_{12}], [S_{12}], [S_{12}]\}$$

$$\mathbf{R}_{25} :: \mathbf{S}_\mathrm{t} = \{[S_1], 3[S_{12}]\}.$$

6.2.6. Emergent shapes

Visual emergence has the capacity to allow designers to look at unexpected or emergent visual structures from what is in front of them. As a consequence, other representations can be developed [36,38]. Emergent shapes are introduced through interpretative and perceptual processes concerned with arriving at alternative description of the shape and a transformational process that uses the existing pattern for generating new structures in a variety of ways [39]. Alternative groupings of subshapes, consisting of the intersections of infinite maximal lines, provide ways to arrive at alternative descriptions of the shape and generate new structures under which new emergent shapes are developed. Examples of emergent shapes are illustrated in Fig. 17(a) and (b) that show emergent shapes as a result of the process of visual emergence but not necessarily as may be perceived by human observers. The description of the symbolic representations for both $\mathbf{R}_{26}$ and $\mathbf{R}_{27}$ are where $\mathbf{S}_\mathrm{e}$ refers to the new constructed emergent representation:

$$\mathbf{S}_\mathrm{e} = \{[i_{na}, i_{ab}, i_{bc}, i_6, i_{mn}], [i_{bc}, i_{cd}, i_2, i_1, i_6],$$
$$[i_{de}, i_{ef}, i_{fg}, i_2, i_{cd}], [i_{fg}, i_{gh}, i_4, i_3, i_1], [i_{hj}, i_{jk}, i_{km}, i_4, i_{gh}],$$
$$[i_{km}, i_{mn}, i_6, i_5, i_4], [i_1, i_2, i_3, i_4, i_5, i_6]\}$$

$$\mathbf{S}_\mathrm{e} = \{[x_1, x_2, x_{11}, x_{11}, x_2], [x_3, x_{11}, x_{11}, x_{11}, x_{11}],$$
$$[x_1, x_2, x_{11}, x_{11}, x_2], [x_3, x_{11}, x_{11}, x_{11}, x_{11}],$$
$$[x_1, x_2, x_{11}, x_{11}, x_2], [x_3, x_{11}, x_{11}, x_{11}, x_{11}],$$
$$[x_{11}, x_{11}, x_{11}, x_{11}, x_{11}, x_{11}\}$$

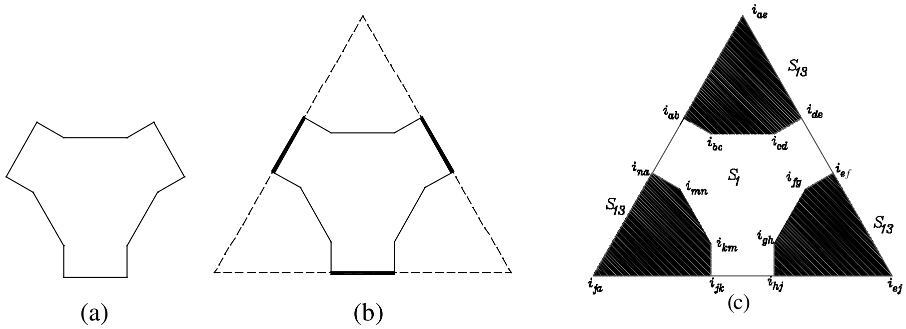


Fig. 15. An example of figure and ground representation ($\mathbf{R}_{24}$) using the outermost convex hull method.

$$\mathbf{S}_e = \{[S_{14}], [S_{15}], [S_{14}], [S_{15}], [S_{14}], [S_{15}], [S_{16}]\}$$

$$\mathbf{R}_{26} :: \mathbf{S}_e = \{3[S_{14}], 3[S_{15}], [S_{16}]\}$$

$$\begin{aligned}\mathbf{S}_e = \{&[i_{na}, i_{ab}, i_{bc}, i_6, i_{mn}], [i_{bc}, i_{cd}, i_1], [i_{cd}, i_2, i_1], [i_{bc}, i_1, i_4],\\ &[i_{de}, i_{ef}, i_{fg}, i_2, i_{cd}], [i_{fg}, i_{gh}, i_3], [i_{fg}, i_3, i_2], [i_{gh}, i_3, i_6],\\ &[i_{hj}, i_{jk}, i_{km}, i_4, i_{gh}], [i_{km}, i_{mn}, i_5], [i_{km}, i_4, i_5], [i_{mn}, i_5, i_6],\\ &[i_1, i_2, i_3, i_4, i_5, i_6]\}v\end{aligned}$$

$$\begin{aligned}\mathbf{S}_l = \{&[x_1, x_2, x_{11}, x_{11}, x_2], [x_3, x_{11}, x_{11}], [x_{11}, x_{11}, x_{11}],\\ &[x_{11}, x_{11}, x_{11}], [x_1, x_2, x_{11}, x_{11}, x_2], [x_3, x_{11}, x_{11}],\\ &[x_{11}, x_{11}, x_{11}], [x_{11}, x_{11}, x_{11}], [x_1, x_2, x_{11}, x_{11}, x_2],\\ &[x_3, x_{11}, x_{11}], [x_{11}, x_{11}, x_{11}], [x_{11}, x_{11}, x_{11}],\\ &[x_{11}, x_{11}, x_{11}, x_{11}, x_{11}, x_{11}]\}\end{aligned}$$

$$\begin{aligned}\mathbf{S}_l = \{&[S_{14}], [S_{18}], [S_{17}], [S_{17}], [S_{14}], [S_{18}], [S_{17}], [S_{17}], [S_{14}],\\ &[S_{18}], [S_{17}], [S_{17}], [S_{16}]\}\end{aligned}$$

$$\mathbf{R}_{27} :: \mathbf{S}_l = \{3[S_{14}], 3[S_{18}], 6[S_{17}], [S_{16}]\}.$$

6.3. Recognising shape semantics from multiple representations

The outcome of recognising shape semantics from each of the 32 developed representations of the same design composition is illustrated in Table 1. Some of these developed representations are represented graphically in the previous Sections 6.2.1 to 6.2.6. The notations used in Table 1 are as follows: $\mathbf{C}_e$, centrality; $\mathbf{D}_m$ dominance; $\mathbf{P}_l$ repetition in length; $\mathbf{P}_p$ repetition of a shape; $\mathbf{P}_r$ repetition in rotation; $\mathbf{R}_c$ closed cyclic rotation of contiguous shapes; $\mathbf{R}_n$ closed cyclic rotation of non-contiguous shapes; $\mathbf{R}_s$ rotation of a shape; $\mathbf{S}_n$ anti-reflective symmetry of a shape; $\mathbf{S}_r$ reflective symmetry around one axis; $\mathbf{S}_t$ reflective symmetry around more than one axis; and $\mathbf{T}_r$ radiality.

6.4. Situated learning from multiple representations

Situated learning in designing can be viewed as acquiring the design knowledge in focus associated to its situation. Situation could be conceived as having several interdependent components, so that the situation is a system of interdependent parts [40]. What makes one situation different from or similar to other situations are the relationships that express relevant distinctions to be made among situations. The regularity where design knowledge in focus operates characterises its situation. The importance of this regularity lies in the development of coherent distinctions among situations [41]. The approach of learning knowledge in focus in relation to its situation makes that knowledge situation sensitive and dependent. The notion of learning the knowledge in focus in relation to its situation maps onto the notion of foreground and background learning where the knowledge in focus forms the foreground while the situation composes the background. The relationships among these shape semantics at different representations are the keys to constructing their situatedness. A learning

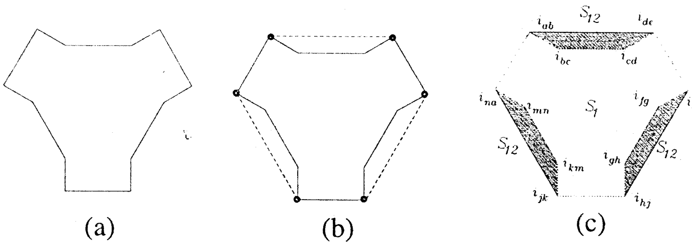
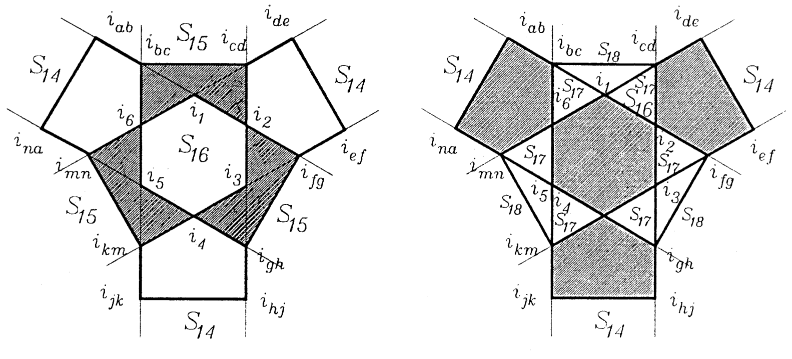


Fig. 16. An example of figure and ground representation ($\mathbf{R}_{25}$) using standard convex hull method.



(a): $\boldsymbol{R_{26}}$ (a): $\boldsymbol{R_{27}}$

Fig. 17. Examples of two developed representations, $\mathbf{R}_{26}$ and $\mathbf{R}_{27}$, from the emergent shapes as a result of an emergence process.

system can construct the situatedness of shape semantics as follows:

1. Picks a single shape semantic and considers it as a knowledge in focus;
2. Finds all the representations where this shape semantic has been recognised;
3. Finds other shape semantics in these representations in conjunction with the knowledge in focus;
4. Finds the regularities of relationships among these shape semantics in conjunction with the knowledge in focus across the representations; and
5. Constructs the situatedness of the design knowledge in focus based on its regularities in conjunction with other shape semantics.

Assuming that a single recognised shape semantic is labelled $\mathbf{k}_i$ and when it is selected to be the knowledge in focus it will be referred to as $\mathbf{F}_j$ and its learned situation as $\mathbf{t}_n$. Applying the above procedures with the set of developed representations and the recognised shape semantics at each one of them as shown in Table 1, if $\mathbf{k}_1$ which refers to centrality ($\mathbf{C}_e$) is selected to be the knowledge in focus $\mathbf{F}_1$, we found that $\mathbf{F}_1$ has been recognised in the representations R_{24} to R_{32}. At these representations, there are three kinds of regularities as illustrated in Fig. 18. These regularities reflect the mapping of one to many, one knowledge in focus to many possible situations. This implies that for certain knowledge in focus there might be a number of possible situations within which it could be recognised. The first regularity is found at the representations R_{28}, R_{29}, R_{30}, R_{31} and R_{32}. The second regularity is found at the representations R_{24} and R_{25} while the third regularity is found at the representations R_{26} and R_{27}. In the representations R_{28}, R_{29}, R_{30}, R_{31} and R_{32} where $\mathbf{F}_1$ is selected to be the knowledge in focus, there is regularity of $\mathbf{F}_1$ in conjunction with other shape semantics $\mathbf{k}_2$, $\mathbf{k}_3$ and $\mathbf{k}_4$ referring to reflective symmetry ($\mathbf{S}_r$), rotation ($\mathbf{R}_s$) and dominance ($\mathbf{D}_m$), respectively. This regularity of relationships defines the

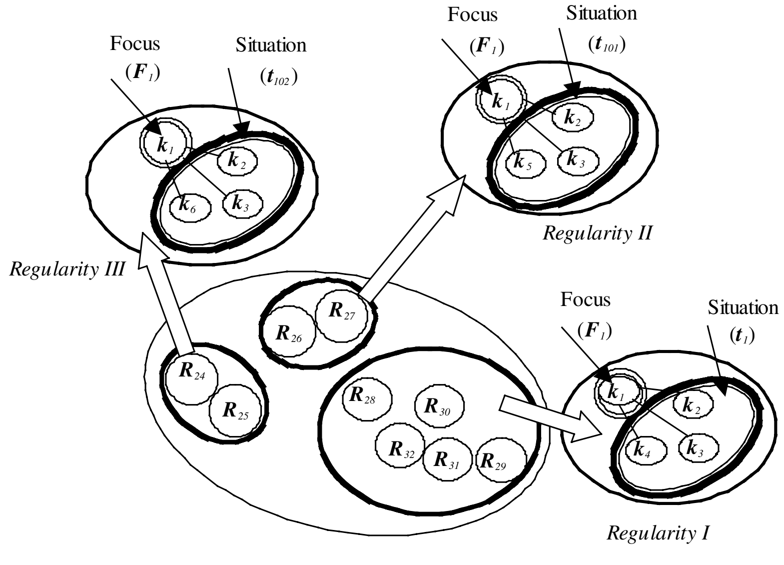


Fig. 18. An example of learned regularities of relationships among shape semantics across some of the representations shown in Table 1 and examples of some of the possible situations ($\mathbf{t}_1$, $\mathbf{t}_{101}$ and $\mathbf{t}_{102}$) for the knowledge in focus ($\mathbf{F}_1$).

Table 2
An example of knowledge in focus ($\mathbf{F}_1$) and its situation ($\mathbf{t}_1$) within the first learned regularity shown in Fig. 18

R_I	Focus $\mathbf{F}_1$	Situation $\mathbf{t}_1$
R_{28}		
R_{29}		$\mathbf{k}_2$ Reflective symmetry around one axis, $\mathbf{S}_r$
R_{30}	$\mathbf{F}_1$	$\mathbf{k}_3$ Rotation of, $\mathbf{R}_s$
R_{31}	$\mathbf{k}_1$ Centrality $\mathbf{C}_e$	$\mathbf{k}_4$ Dominance of, $\mathbf{D}_m$
R_{32}		

Table 3
An example of the duality between the knowledge in focus and its situation with the first learned regularity as shown in Fig. 19

R_I	Focus $\mathbf{F}_4$	Situation $\mathbf{t}_4$
R_{28}		
R_{29}		$\mathbf{k}_1$ Centrality, $\mathbf{C}_e$
R_{30}	$\mathbf{F}_4$	$\mathbf{k}_2$ Reflective symmetry around one axis, $\mathbf{S}_r$
R_{31}	$\mathbf{k}_4$ Dominance of $\mathbf{D}_m$	$\mathbf{k}_3$ Rotation of, $\mathbf{R}_s$
R_{32}		

situation within which $\mathbf{F}_1$ was recognised and constructs its situation $\mathbf{t}_1$. This means that centrality ($\mathbf{C}_e$) is situated within reflective symmetry ($\mathbf{S}_r$), rotation ($\mathbf{R}_s$) and dominance ($\mathbf{D}_m$). Table 2 illustrates this relationship between the knowledge in focus $\mathbf{F}_1$ and its situation $\mathbf{t}_1$ found at the representations R_{28}, R_{29}, R_{30}, R_{31} and R_{32}.

The second regularity is found at the representations R_{24} and R_{25}. If $\mathbf{k}_1$ which refers to centrality ($\mathbf{C}_e$) is selected to be the knowledge in focus $\mathbf{F}_1$, we found that there is regularity of $\mathbf{F}_1$ in conjunction with other shape semantics $\mathbf{k}_2$, $\mathbf{k}_3$ and $\mathbf{k}_5$ where $\mathbf{k}_5$ refers to radiality ($\mathbf{T}_r$). This regularity of relationships constructs a second situation $\mathbf{t}_{101}$ within which $\mathbf{F}_1$ was recognised. A third regularity is found at the representations R_{26} and R_{27}. Once again, if $\mathbf{k}_1$ which refers to centrality ($\mathbf{C}_e$) is selected to be the knowledge in focus $\mathbf{F}_1$, we found that there is regularity of $\mathbf{F}_1$ in conjunction with other shape semantics $\mathbf{k}_2$, $\mathbf{k}_3$ and $\mathbf{k}_6$ where $\mathbf{k}_6$ refers to closed cyclic rotation ($\mathbf{R}_c$). This regularity of relationships constructs a third situation $\mathbf{t}_{102}$ within which $\mathbf{F}_1$ was recognised. This means that there is more than one situation within which $\mathbf{F}_1$ could be recognised.

Alternatively, in the first regularity if another shape semantic $\mathbf{k}_4$ which refers to dominance ($\mathbf{D}_m$) is selected to be the knowledge in focus $\mathbf{F}_4$ we found that $\mathbf{k}_1$, $\mathbf{k}_2$ and $\mathbf{k}_3$ construct its situation $\mathbf{t}_4$ as shown in Table 3 and Fig. 19. This could be explained as duality between knowledge in focus and its situation. This implies that for certain knowledge in focus $\mathbf{F}_1$ recognised in a situation $\mathbf{t}_1$ where $\mathbf{F}_4$ is part of $\mathbf{t}_1$ it is possible that whenever $\mathbf{F}_4$ is the knowledge in focus that $\mathbf{F}_1$ would be part of its situation $\mathbf{t}_4$. Similarly

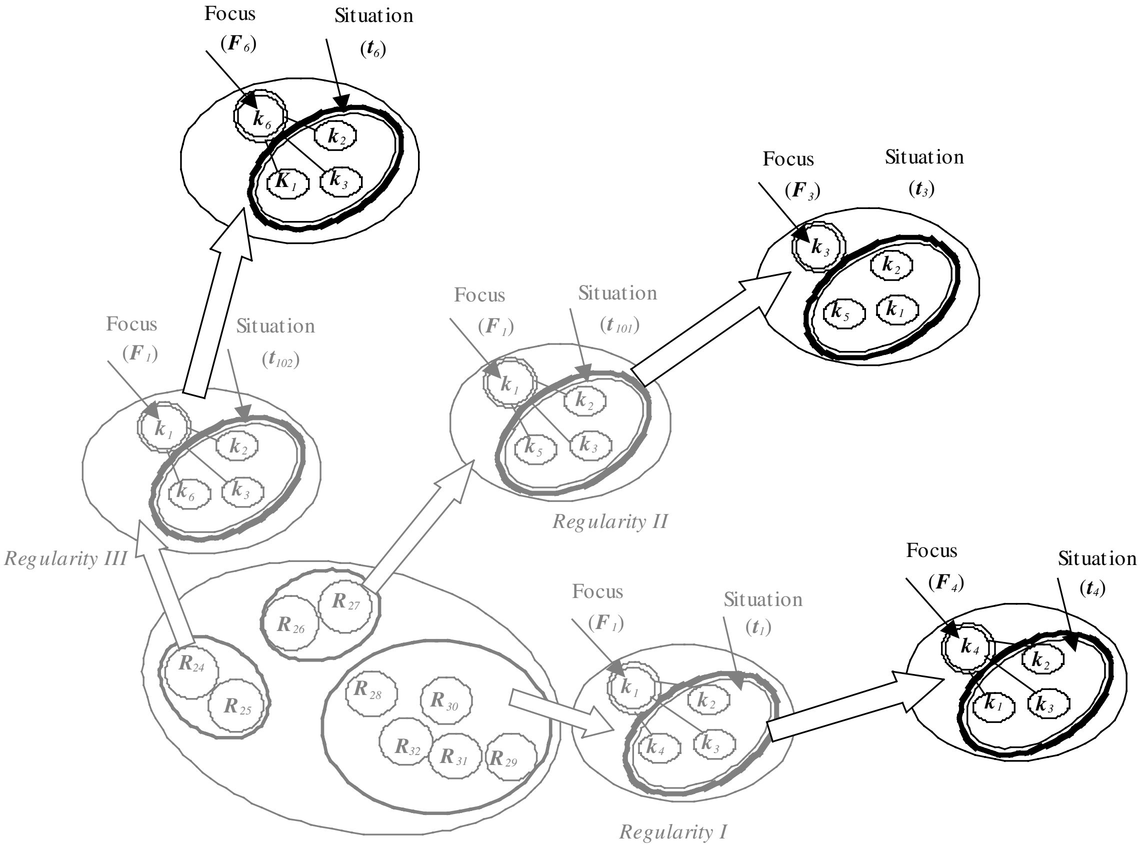


Fig. 19. Examples of the duality between knowledge in focus and the situation within the learned regularities of relationships among shape semantics shown in Fig. 18.

this could be applied with the other two regularities as shown in Fig. 19.

An other important result that can be derived from Table 1 is an associative relationship between the shape semantics $\mathbf{k}_2$ and $\mathbf{k}_7$ where $\mathbf{k}_7$ refers to repetition ($\mathbf{P}_\mathrm{p}$) at the representations R_{13}, R_{15}, R_{16}, R_{18} and R_{19}. If $\mathbf{k}_7$ is selected to be the knowledge in focus $\mathbf{F}_7$ then no conclusion can be made about its situation. This shows the importance of various representations to discover relationships among shape semantics to construct their situatedness based on the situations within which they were recognised.

7. Discussion

Viewing designing as a situated activity whereby the situatedness of design knowledge is not determined a priori but rather constructed while designing coincides with how the activity of designing is observed by design researchers [2,12]. In this respect designing is situated while designers draw and observe their designs. Situations are not preset but constructed on the fly based on need. Thus, for design knowledge to be useful it needs to be learned in relation to the situation within which it was recognised. On the other hand, situation or context free learning in designing, like any other method that tries to learn abstract concepts independently of the situation, overlooks the way learning is developed through continued and situated use.

In this paper the notion of situatedness is introduced within the domain of visual perception of a design composition, however, it is applicable to other sorts of designing activities. Situated learning is concerned with learning the regularities of relationships among shape semantics in order to construct their situatedness within which they were recognised across different representations. Multiple representations allow for diverse interpretations that might be put to use at various states during the design process. Multiple representations provide a medium within which various shape semantics and relationships among them are recognised. Multiple representations show potential advantages as a platform for situated learning in designing and as a mechanism that helps to generate different views of a design composition within which various situations might be encountered. The situatedness of design knowledge has the potential to provide the basis for guiding the use of that knowledge. For instance, in a situation where $\mathbf{R}_\mathrm{s}$, $\mathbf{S}_\mathrm{r}$ and $\mathbf{D}_\mathrm{m}$ exist then we would be able to apply $\mathbf{C}_\mathrm{e}$ based upon what was learned previously. Similarly, if $\mathbf{C}_\mathrm{e}$, $\mathbf{R}_\mathrm{s}$ and $\mathbf{S}_\mathrm{r}$ exist in a situation then we would be able to apply $\mathbf{D}_\mathrm{m}$.

In conclusion, this paper introduced multiple representations as a platform for a system to learn two classes of knowledge: recognise various types of shape semantics from multiple representations through different interpretations of a design composition and learn the regularities of relationships across the recognised shape semantics in the representations. These relationships help to construct the situatedness of shape semantics that has the potential to guide the use of shape semantics in similar situations.

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