14 del 2 al 5 de Diciembre de 2008
CONVENCIÓN CIENTÍFICA DE INGENIERÍA Y ARQUITECTURA
44 ANIVERSARIO cujae 2008
Congreso SIGraDi Cuba 2008
Gráfica Digital Integración y Desarrollo
La Habana 1 al 5 Diciembre 2008

COMPUTING AND MANIPULATION IN DESIGN
A PEDAGOGICAL EXPERIENCE USING SYMMETRY

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Abstract. **This paper discusses the development of a cognitive experience concerned with the application of the concept of symmetry in the creative generation of forms by 3rd year architectural design students. The experience has involved the use of computational tools associated to symmetry knowledge in three different sets of pedagogical exercises. These are described and analyzed under different aspects such as Discretion/Continuity, Generation of Meta-Shapes, Modes of Representation and Differentiation, Visual Reasoning and Conscious Interaction. The results commented as to conclude that the experience had an important impact in the student's learning process.**

Keywords. **Symmetry, Cognition, Computing, Visual reasoning, Design teaching.**

INTRODUCTION

Intelligence is defined by Minsky [1] as the ability to solve problems. According to Minsky simple problems might be solved trough trial and error, successively generating and testing all possible solutions within a certain universe of possibilities. However this is a very time-consuming method, not suitable for more complicated problems, which might be solved using the 'progress principle'. This method is based in the gradual improvement towards a goal that can be achieved and in whose terms the problem is previously formulated. Architectural design can be described as a hard problem and, as such, it has to be split into smaller problems and formulated in terms of goals and sub goals which can be progressively achieved.

Visual intelligence can be defined, based on Minsky's ideas, as the ability to solve problems involving vision and the perception of planes, lines and shapes, primary and emergent. Primary shapes are the ones explicitly represented and emergent shapes are the ones implicit in the others [2]. Shape emergence is the method to identify them, producing new explicit representations from former implicit shapes[3]. Some groups of shapes are especially meaningful in architecture, expressing visual features so as symmetry, rhythm, movement and balance. Known as Semantic Shapes, they can be differentiated according to the Gestalt Laws – proximity, similarity, good continuation, closure and figure-ground reversal. The creation, recognition and meaning of forms and shapes, aspects of visual reasoning involved in design, constitute therefore sub problems of the architectural design process.

This paper describes a teaching strategy developed since 1995 with 5th semester students in the Design Studio of the Faculty of Architecture at the Federal University of Rio Grande do Sul in Brazil. The teaching strategy correlates these sub problems to a series of exercises aimed at the progressive development of skills to support the term project. Each exercise constitutes a stage of development whereby the student might learn from former stages and that "teaches" the subsequent ones. In this paper we describe three approaches to the creative generation of forms using symmetry operations, corresponding to the experience during different semesters. The creation of symmetry compositions with computational support was combined to other different exercises in each semester. The first approach combined the creation of two-dimensional patterns to their application and to their modeling into three-dimensions. The second approach combined the work with computational support with work with physical models and mirrors and the analysis of the created patterns. And the third approach combined the computational tasks with work with two-dimensional physical shapes and mirrors.

The paper is divided in five parts: in the next section we define the concept of symmetry used in the exercises. In section II materials, methods and examples of the three approaches are presented. The results are analyzed and compared in section III and in the last section conclusions are driven about the contribution of the method to the student's cognitive process.

I. SYMMETRY

The concept of symmetry has been usually been restricted to bilateral symmetry or the reflection with reference to a bilateral axis. In an extended sense symmetry refers to any isometric transformation that maintains a certain shape invariant. According to this notion, the repetition of a certain shape with reference to one or more axis comprises a symmetric composition, which is the result of recursive isometric transformations on a shape. This extended notion represents a tool for the recognition and reproduction of patterns in two or three dimensions. The recognition of patterns and shapes is primal to the perception, comprehension and description of everything that we see, and it influences the development of cognitive abilities inherent to the design process.

Principles of order such as symmetry have been described and used by many architects through history including Alberti, Leonardo da Vinci, Frank Lloyd Wright, Le Corbusier, Oscar Niemeyer and Santiago Calatravra. The incorporation of principles of order in the education of an architect highly affects his worldview and his ability to organize and create. Wright [4] used to say that because of his education he very soon became "capable of perceiving a constructive pattern in everything that (he) saw". According to March and Steadman [5] two of the most innovating architects of the 20th century, Wright and Le Corbusier, were able to innovate owing to their appreciation and profound understanding of concepts such as symmetry and pattern structure.

Since antiquity various types of symmetry patterns constitute a design tool in architecture: e.g. plans, elevations, frameworks; and in the decorative arts: e. g. pottery, tile works, furniture, graphic art and design. In nature rigorous symmetry patterns are found in animals, plants and crystals, e.g. radiolarians, iris, snow flakes.

The concept of geometric symmetry has been formalized in modern mathematics trough the idea of groups of transformations. Patterns defined by symmetry operations or isometric transformations such as translation, rotation, reflection and combinations of these are classified as groups of plane symmetry, in two dimensions, and crystallographic symmetry, in three dimensions. Symmetry patterns may be discrete or continuous, and they may constitute congruent shapes, through isometric transformations, or similar shapes, through stretching. This last case might be exemplified by the symmetry pattern present in many shells, whose shape results from the combination of innumerous rotations with expansions. "The straight line and the circle are the limiting cases of the logarithmic spiral and they result from a combination of rotation and dilatation where one of them defines the identity." [6] The nautilus is a perfect example of this kind of symmetry, such as the organization of the seeds and the layout of the petals of the sunflower.

The groups of planar symmetry are classified according to their structure of translation in point groups, frizes and wallpapers.

There are two types of point groups: the Cn cyclic group, constituted by simple rotations; and the Dn dihedral group, constituted by the combination of rotations and reflections.

There are seven groups of friezes, designated Fn: four of them combine translation and reflection, and three combine translation and rotation. [5]

There are 17 groups of wallpapers, designated Wn.6 Since two distinct vectors are enough to describe a third one, similar to the coordinates that determine a point in the plane, any translation in a single plane might be reduced to two distinct translations T1 and T2. This way any group of plane symmetry will be based on a grid specified by T1 and T2. The greatest number of possible rotations on this grid is 6. [5]

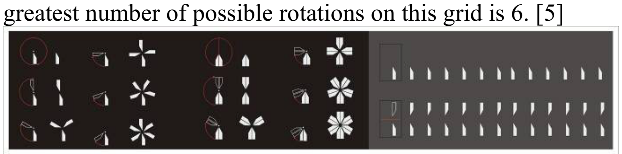

Figure 1.Examples of point groups and friezes

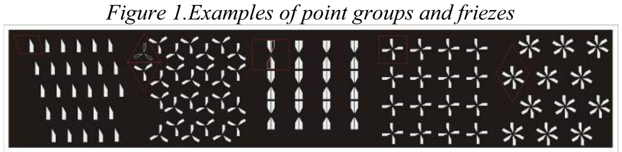

Figure 2. Example of wallpaper groups

The number of groups in every type of symmetry results from the possibilities of organization for each rule. This number is small for symmetries in the plane, but in crystallographic symmetry it raises to 230 different alternatives.

According to Tay Kheng Soong [7], coherent architectural compositions are characterized, among other properties, by "similar, symmetric parts, visually balanced or symmetrically rotated and that, after all, constitute a recognizable pattern of entities that repeat themselves". This definition is similar to another by Poincaré, in answer to the question: "What is it indeed that gives us the feeling of elegance in a solution, in a demonstration? It is the harmony of the diverse parts, their symmetry, their happy balance; it is all that introduces order, all that gives unity that permits us to see clearly and to comprehend at once both the ensemble and the details." [8] Stimulated by ideas such as the ones from Soong and Poincaré, we have proposed a teaching strategy based on the use of concepts of symmetry in the creative exploration of forms.

II. Symmetry Exercises

The idea behind the exercises was to stimulate the development of skills related to the creation, recognition and meaning of forms and shapes through the widened concept of symmetry defined in the previous section. Besides that, a further aim was to offer the students a larger comprehension about the possible use of computational applications in the initial phases of creation, and not just the drafting of projects. For the exploration of compositions based on symmetry operations with computational support we proposed the use of AutoCAD following a method developed by Celani [9]. In order to allow the user to generate, visualize, modify and update symmetrical compositions, Celani proposes two procedures envolving simple commands of AutoCAD.

The first procedure, named "Semi-dynamic Symmetrical Compositions - SSC" [9], consists of the drawing, definition and insertion of 'blocks', which in AutoCAD are entities composed of other entities, and arranging them in symmetrical compositions by rotating, mirroring and serializing them with the commands 'rotate', 'mirror' and 'array'. The further redefinition of the 'block', by modifying its components, their position, rotation or scale, allows for the automatic update of the previously created compositions.

The second method, named "Dynamic Symmetrical Compositions - DSC" [9], uses several 'viewports', which in AutoCAD are windows for the visualization of the drawing, to allow for the simultaneous modification and visualization of the drawn entities arranged in symmetrical compositions.

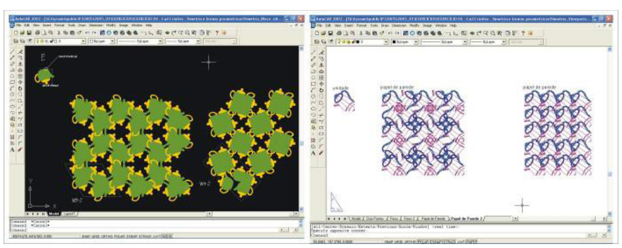

Figure 3. Computational environments for semi-dynamic and dynamic symmetric compositions

The three approaches proposed the creation of symmetry patterns with computational support combined to other different types of exercises. Symmetry exercises were preceded by two other exercises described in Westphal et. Al. [10], involving the transformation of functional objects and that might provide the initial shape for the subsequent tasks. For the computational exercise two preconfigured AutoCAD files were provided for the students, one with several symmetry groups drawn using the SSC method, the other with some symmetry groups arranged in the DSC method. The preconfigured files allowed the students to explore different symmetrical arrangements by redefining the initial unit of the preconfigured patterns, what required no profound knowledge of the computational application. The approaches described next correspond to the experience realized in the first semester of 2005, in the second semester of 2006 and in the second semester of 2007.

1.i. First approach – Materials and Method

In the first approach the exercises on symmetry were carried out in four stages. The first stage consisted in the creation of two-dimensional compositions with computational support, departing from the student's functional object or from its transformations. The students should draw the chosen object in AutoCAD, whether as a three-dimensional model, represented in one of its vistas, or represented trough pictures taken from it.

The second stage comprised the exploration of possible applications for the created patterns, suggesting different uses for the compositions by inserting them in several settings through drawings, pictures and montages.

The third stage of the exercise was the three-dimensional modeling of the symmetry patterns aiming to increase the students' awareness over the possibilities for the generation of volumes departing from the originally two-dimensional patterns. The students were advised to try to visualize the borders of different horizontal planes in the shapes of their symmetry patterns. These shapes could also originate vertical planes or serve as guidelines for the sliding or tilting of the horizontal planes. In this stage the students were stimulated to create three-dimensional compositions without reference to any functions or architectural brief.

In the fourth stage we proposed the exploration of three-dimensional compositions departing from the two-dimensional patterns and assigning functions and uses to the forms and spaces created. Without having a preconceived brief, the students should visualize possible uses for the created spaces. In this way the emergence of functions was expected to work as a catalyst of the three-dimensional composition. If on the one hand the existing shapes could suggest a function, on the other hand the relation between a proposed function and the possible arrangements of lines and planes could guide the students to identify in the patterns the best geometrical solution for the desired use.

1.ii. Composition with Computational Support – Examples

Examples 1, 2 and 3 are originated in a transformation of a vinyl disc, creating the form of a seat that was drawn in the preconfigured DSC file. The arranged 'viewports' were slightly overlapped, generating continuous W4 type patterns. Examples 4 and 5 are originated from transformations made with a CD case, creating W2 type patterns with the same method. Examples 6 and 7 are W4 type patterns and friezes generated with DCS and departing from the side view of a VHS tape case.

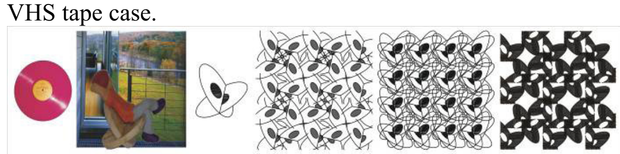

Figure 4. Object, form exploration, unit, examples 1 – 2 – 3 (Raquel Greve)

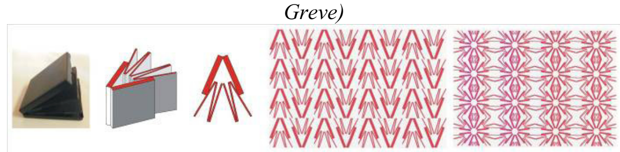

Figure 5. Object, form exploration, unit, examples 4 – 5 (Carlos Weidlich)

Figure 6. Object, unit, examples 6 – 7 (Franciele Granada)

Examples 8 and 9 are both W4 type patterns created with the use of the SSC preconfigured file departing from cassette cases. Example 8 is a three-dimensional wire frame representation of the case and example 9 uses shaded planes for the object's faces. Examples 10, 11 and 12 were generated with the SSC method departing from the side view of a VHS tape case. Compositions 10 and 11 are W6 type patterns and example 12 is a W3-2 type wallpaper. Examples 13 to 15 were created with the same method and are originated from the side view of a match box. Example 13 is a W2-2 type wallpaper, example 14 is a W2 type and example 15 a W3-2 type pattern.

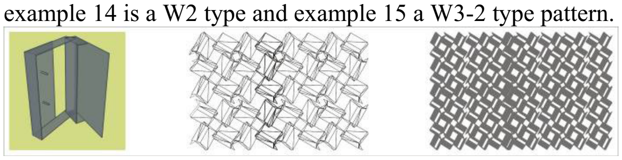

Figure 7. Object, examples 8 – 9 (Marcelle Bridi)

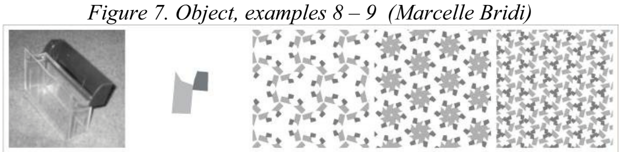

Figure 8. Object, unit, examples 10 – 11 – 12 (Juliana Parise)

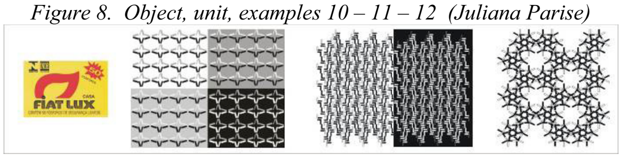

Figure 9. Object, examples 13 – 14 – 15 (Paola Escuder)

1.iii. Application – Examples

Example 16 reproduces a W2 type pattern generated from a CD case applied as tiles. Example 17 simulates the use as a cloth print of a W4 type pattern generated from the top view of a kaleidoscope. Both examples were created using the DSC method. Examples 18, 19 and 20 were originated from a cassette case using the SSC method. The first one simulates the use of a C5 type pattern as a tattoo. Example 19 proposes the same pattern and a F1 type frieze as T-shirt prints. And example 20 simulates the application of a W2-3 type pattern as ceiling fixtures in a concert stage.

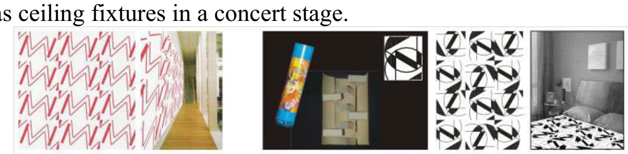

Figure 10. Pattern, example 16 (Carlos Weidlich) Object, form exploration, pattern example 17 (Camila Bernadeli)

Figure 11. Object, pattern, example 18 – Pattern, example 19 – Pattern, example 20 (Marcelle Bridi)

1.iv. Three-Dimensional Composition – Examples

Example 21 was originated from a W1 type symmetry pattern and built with superposed discs of glycerin soap. With illumination from behind, the original symmetry pattern emerges as a result of the materials' transparency. Example 22 departed from the transformation of a CD case suggesting the opening of its cover, originating a W3 type symmetry pattern. The pattern was unfolded in a three-dimensional composition reproducing the idea of movement.

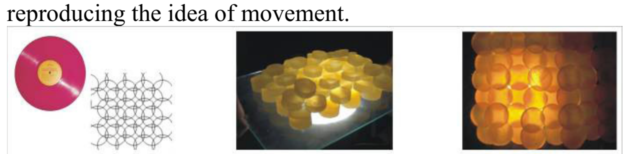

Figure 12. Object, pattern, example 21 (Raquel Greve)

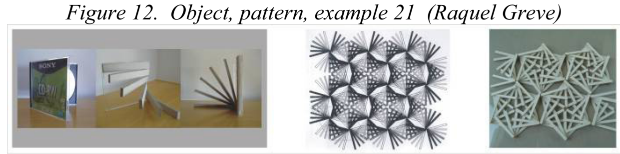

Figure 13. Object, form exploration, pattern, example 22 (Sandra Becker)

1.v. Emergent Function – Examples

Example 23 departed from a W4 type pattern generated from the transformation of a soap box. The spaces created from the pattern were assigned to residential functions such as living, dressing, cooking and eating.

Example 24 used a W4 type pattern as well, originated in the side view of a foldable makeup container. The student extracted part of the pattern, defining horizontal and tilted planes in two levels. The lower level was designated for working and resting, the upper level for studying and sleeping and the tilted planes would be ramps. The lines from the pattern originated the subdivision of the internal space and guided the shape of the horizontal and tilted planes.

Figure 14. Object, form exploration, pattern, example 23 (Fabrícia Grando)

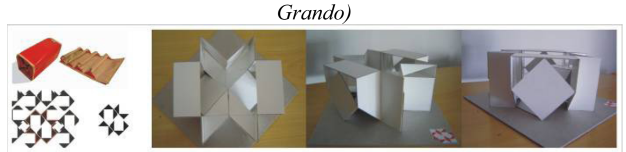

Figure 15. Object, pattern, example 24 (Vanessa Zechin)

2. Second Approach – Materials and Method

In the second approach the exercises on symmetry were carried out in three stages. The first stage comprised the exploration of symmetry compositions using physical models and mirrors in order to familiarize the students with the basic symmetry operations before the exercises with computational support. The students were stimulated to explore symmetrical compositions using mirrors and taking pictures of the created patterns. With flat mirrors they could make dihedral compositions, friezes and wallpapers based on reflection. The students should use physical models from the functional objects they chose for the previous exercises. The students could create three-dimensional compositions with computational support as well, using virtual models of their functional objects.

The second stage consisted in the creation of symmetry compositions with computational support using the preconfigured SSC and DSC AutoCAD files departing from the students' functional object or from any shape chosen at will.

In the third stage the students should analyze the compositions formerly created, describing them in terms of initial unit, symmetrical arrangement, primary and emergent shapes and their visual properties. The students were stimulated to identify properties based on the gestalt laws and semantic features such as visual movement, rhythm, balance. This activity was supported by lectures on these specific subjects.

2.i. Composition with Physical Models and Mirrors – Examples

Examples 25 to 28 departed from an ink cartridge, and the exercise was done with a white model of the deformed object. The object was placed on a horizontal mirror and in the internal angle of two vertical mirrors forming a corner. Example 25 is a D4 type pattern, example 26 is a D6 type pattern, examples 27 and 28 are both D9 type patterns.

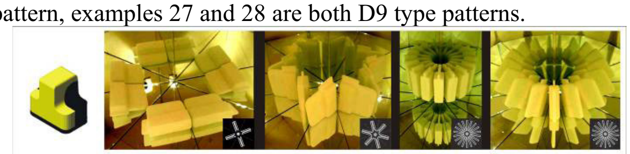

Figure 16. Object, examples 25 – 26 – 27 -28 (Luciana Tissot)

Examples 29 to 33 departed from the model of a shampoo bottle, reflected with three mirrors, and they are respectively a D1.5, a D3, a D4 and two D5 symmetry patterns.

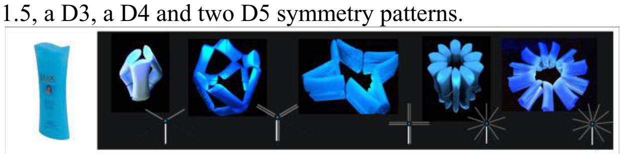

Figure 17. Object, example 29 – 30 – 31 – 32 – 33 (Martina Jacobi)

Examples 34 to 37 departed from a deformed dental floss case that originated several patterns using mirrors as well. Example 34 is a D3 type composition, examples 35 and 36 are D4 type patterns, all created with the use of three mirrors. Example 37 is a model of urban landscape, where the buildings were substituted by models derived from deformations of the functional objects used in the exercises. With four parallel mirrors the model was infinitely reflected, simulating a wide urban landscape.

Figure 18. Object, example 34 – 35 – 36 – 37 (Vicente Silva)

2.ii. Composition with Computational Support – Examples

Examples 38 to 40 are compositions departing from a perfume bottle, created in the computational environment using the SSC method. Examples 38 and 39 are both W2 wallpapers and example 39 is a W2-2 composition.

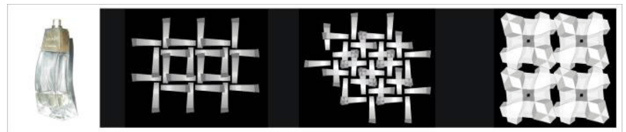

Figure 19. Object, examples 38 – 39 – 40 (Karen Quednau)

Examples 41 to 44 were made with computational support as well, departing from the model of a Phillips-head screwdriver. Example 41 is a C11 cyclic group. Example 42 is composed of two partially overlapped W3-1 symmetry patterns, in different heights. Example 43 simulates the reflection of a W3 pattern on a horizontal mirror. And example 44 is a variation of a W1-2 pattern, suggesting movement trough the use of height differences forming waves.

Figure 20. Object, examples 41 – 42 – 43 – 44 (Bruno De Lazzari)

Examples 45 to 47 are two-dimensional compositions created with computational support using the DSC method. The patterns departed from simple shapes that the student has drawn in the preconfigured file. Example 45 is a W2 pattern originated from scaled circular shapes. Examples 46 and 47 departed both from scaled curvilinear shapes, arranged respectively in a W2 and a W4 wallpaper symmetry pattern.

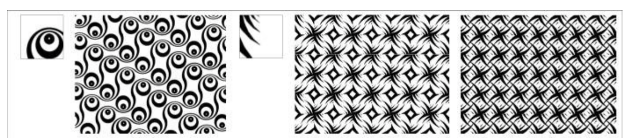

Figure 21. Unit, example 45, unit, example 46 – 47 (Bruno De Lazzari)

2.iii. Analysis – Examples

Example 48 departed from a pattern created by the student using two triangles as the initial shape and combining several symmetry operations, without strictly following the symmetry groups. The student decomposed the pattern in its primitive shape and demonstrated various types and sizes of emergent shapes.

Figure 22. Example 48 - unit, pattern, primitive shapes, emergent shapes (Tiago Bitelo)

Example 49 is the identification of emergent shapes such as squares, rectangles and lines in a pattern originated from a W4 type symmetry pattern. The analyzed pattern departed from the side view of a shampoo bottle, the same functional object that originated examples 29 to 33.

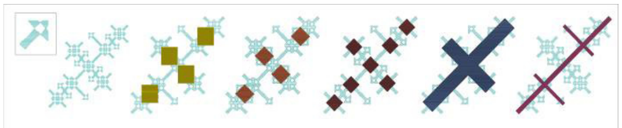

Figure 23. Example 49 – unit, emergent shapes (Martina Jacobi)

Example 50 is the analysis and decomposition of a W4 symmetry pattern originated from the side view of a computers mother-board. The student identified primitive and emergent shapes, and semantic properties such as visual movement and visual rhythm.

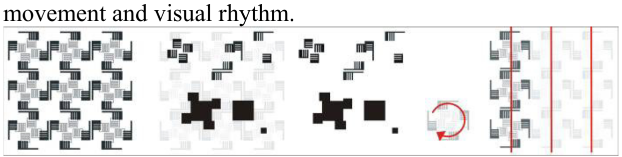

Figure 24. Example 50 – pattern, primitive and emergent shapes, visual movement, visual rhythm (Simone Coracini)

3. Third Approach – Materials and Method

In the third approach the exercises on symmetry were carried out in two stages. The first stage was the creation of compositions with symmetry operations with cardboard pieces based on the *Tangram*. The students used 14 pieces of cardboard in basic shapes such as squares, triangles and lozenges, in one or more colors. They should create compositions with the shapes only and using mirrors as well, being stimulated to explore visual features such as movement, rhythm, balance, figure/ground, color, emergence, etc.

The second stage was the creation of symmetry compositions in the computational environment using the preconfigured SSC and DSC AutoCAD files and departing from the *Tangram* shapes or from any other shapes.

3.i. Exercises with the Tangram – Examples (Stages 1 and 2)

Examples 51 to 53 are C2 type point symmetries, example 54 is a D2 type pattern using the composition from the previous example, and example 55 is a D3 type pattern. Examples 51 and 53 explore visual balance and emergence from the ground, example 52 denotes visual movement, while example 55 transmits static.

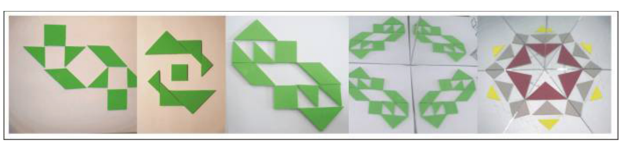

Figure 25. Example 51 – 52 – 53 – 54 – 55 (Luisa Krawczyk)

Examples 56 and 57 are F2-1 type patterns were the student compared similar patterns with different distances between the shapes. While in example 56 the initial shapes are grouped forming new shapes according to their color, in example 58 the initial shapes are separated but aligned, allowing for the emergence of orthogonal lines from the ground. Both compositions explore the visual property of balance. Example 58 is a W4 wallpaper and example 59 is a W3 type pattern, both created with the SSC method departing from a unit composed of triangles exploring visual movement trough variations in color and scale.

Figure 26. Unit, example 56, unit, example 57, unit example 58 – 59 (Fani Eischelberger)

Examples 60 and 62 are compositions based on symmetry operations are not restricted to the groups of symmetry. Both are compositions where the student used an organization based on groups of symmetry but without strictly following the rules of symmetry. Based on a D2 type pattern, example 60 explores the property of visual closure, since the surrounding ring of triangles is actually open, but it is visually completed by the addiction of a square in the lower left corner of the composition. Example 61 is a very variation of a C4 symmetry pattern, whose is not obvious at first sight. However the simple replacement of the triangle to the left by a square reveals the symmetry pattern behind the composition. Example 61 is a F2 frieze departing from the composition in example 60. And example 63 is a W4 type wallpaper pattern based in the composition from example 62. Created using the SSC method, both compositions are in two colors, according to the shape, affecting the perception of emergent shapes from the patterns.

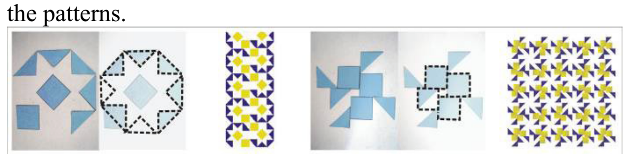

Figure 27. Examples 60 – 61 – 62 – 63 (Marcos Petroli)

Examples 64 and 67 are C4 point groups exploring visual movement, example 65 is a C2 type symmetry exploring balance and example 65 is a variation of F1 frieze with an inflection. Examples 67 to 69 use the same unit, a composition of three triangles exploring minimalism, emergence and figure-ground in the preconfigured SSC file. Example 67 is a C4 point group, example 68 is a W3 symmetry pattern and example 69 is W4 wallpaper.

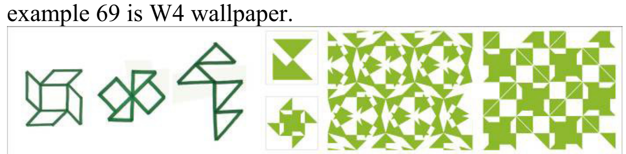

Figure 28. Example 64 – 65 – 66, unit, example 67 – 68 – 69 (Lucas da Veiga)

III. Analysis

The student's work can be analyzed under different aspects. The chosen aspects were: Discretion/Continuity, Generation of Meta-Shapes and Modes of Representation and Differentiation, Visual Reasoning and Conscious Interaction.

1. Discrete/Continuous Patterns

Discrete patterns are those whose components are perceived as isolated groups (examples 6, 10, 13, 18, 20, 61, 63); Continuous patterns are those whose components merge and/or overlap to one another (examples 1-5, 7-9, 11-12, 14-

17, 19, 38-40, 42-48, 50, 58, 59, 68, 69). Compositions with discrete groups of shapes generated too simplified patterns As opposed to the compositions in continuous friezes or wallpapers which seem to be more elaborated. With the DSC method, discretion and continuity rely on the represented object's size in relation to the viewport size. Small generative shapes originated patterns composed of isolated groups, while larger generative shapes are partially hidden by the viewport, affecting the merging potential of the pattern. The continuity of the pattern through the merging and/or overlapping of shapes depend on the redefinition of the pre configured file, rearranging and previously overlapping the viewports. On the other hand in the SSC method the discretion/continuity of the pattern is relative to the distance between the previously inserted blocks. As the generative shape is never sectioned or hidden, different relations between elements might be tested in the same pre configured file.

2. Generation of Meta-shapes

Meta-shapes are resulting shapes which arise from particular geometrical combinations of generative elements. The generation of meta-shapes from the symmetrical arrangement is clearly dependent on the relation between the geometry of the generative shape and the geometrical structure of the symmetrical arrangement. The compositions where meta-shapes are formed apparently are more elaborated (examples 39-40, 45-49, 58, 59, 67-69).

3. Modes of Representation and Differentiation

The computational results seem to have been influenced not only by the different generative shape, but also by modes of representation that the students have used. The best results were generated from shaded gradient surfaces (examples 3, 13, 38-40), exploring contrast (examples 45-48, 67-69), combining colors (58, 59, 61, 63) and combining shaded surfaces and lines (examples 1, 2, 4). The exclusive use of lines or uniformly shaded surfaces seems to affect results in this aspect (examples 8, 9). In the case of the work departing from functional objects (sets 1 and 2), the student had to choose the objects' orientation and relative position to the applet's system of coordinates. Along with the multiple symmetrical arrangements, this allowed students departing from similar objects to generate different patterns, such as the examples originated from the side view of a VHS tape case (examples 6-7 and 10-11).

4. . Visual Reasoning

The derivation of three-dimensional compositions from a two-dimensional pattern was, initially, a difficult task. The initial difficulty in the exploration of three-dimensional compositions suggested that the students might have a limited visual repertoire. With the progressive recognition and identification of patterns, the students demonstrated an increased repertoire, assigning well-known functions to very innovative forms and spaces. This statement reinforces the initial hypothesis about the importance of the exploration of the concepts of symmetry in the cognitive design process. While assigning innovative forms to well-known functions, the students acquired composition strategies that would be further used in the resolution of several types of architectural briefs.

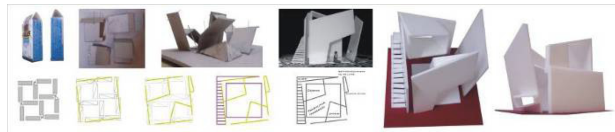

Figure 29. Object, pattern, sketches, exercise of emergent function (Cássio Sauer)

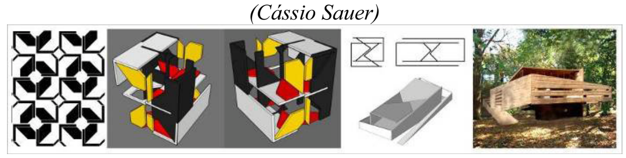

Figure 30. Pattern, exercise of emergent function, term project (Miguel Esnaola)

5. Conscious Interaction

In the second approach, the first stage with mirrors allowed different possibilities for compositions based on reflection. Several variations could be obtained by just altering the disposition of the mirrors. With an object placed between two vertical mirrors, the smaller the angle, the more repetitions are obtained, and the resulting composition approximates a cylinder (examples 27, 32). With parallel mirrors surrounding the initial object (example 37) infinite wallpapers or friezes might be obtained. As with the computational method, the results depend on the relation between the geometry of the objects and the disposition of the mirrors. When the object is placed lying on a horizontal mirror, the organization of the resulting composition will be explicitly planar (examples 25-27, 31-33). With a tilted object more elaborate compositions are possible, sometimes even creating internal spaces (examples 29, 30, 34, 36).

In the third set, the work based on the *Tangram* has stimulated the students to explore several visual properties in their compositions including visual balance, movement, emergence, figure/ground reversal, closure, color, and others. The use of mirrors has again allowed the students to explore the relation of the geometry of the generative shape and the arrangement of the created pattern. Besides, the use of primitive shapes such as squares and triangles has increased the potential for new combinations or meta-shapes by juxtaposition and reflection. This could be observed in the compositions created in the computational environment as well. At the second set, the identification of emergent shapes and visual features such as movement and rhythm has led some students to remake their symmetry compositions after the third stage, in order to obtain better results at the second one. This has shown that the method provokes a continuous feed back and a permanent "back and forth" movement in the designer's decision making process.

The combination of the work using physical shapes and mirrors with the computational applications produced better results than in the first set. The use of mirrors has also improved the students understanding over the relation between the geometry of generative shape and the geometrical structure of the arrangement involved in the composition, resulting in more elaborated patterns at the computational stage. In the second and in the third set, the use of mirrors and models inspired a better interaction and a more conscious generation of three-dimensional compositions, stimulating the use of the computational environment with 3D models as well.

IV. Conclusions

The described experiences have shown that symmetry concepts combined with a computational applicative may give rise to new ways of creative exploration of shapes.

The conscious analysis of the created patterns enhanced the student's understanding over the concept of symmetry and over the different semantic possibilities involved in the exploration of forms and shapes in two or three dimensions. This way, both the conscientious creation and the conscientious analysis of the compositions have stimulated the elaboration of meaning. The method has allowed the students to develop both syntactic and semantic aspects of visual reasoning, enhancing their visual repertoire and helping them to create a meaningful pathway in the design process, from the conceptual sketches to the term project.

The enhancement of the students' repertoire constitutes an important strategy in the building of the cognitive abilities used in the architectural design process. The widened understanding of symmetry, along with other tools related to the understanding of the syntax and the semantic aspects of form turn out as key factors for the acquisition of these abilities. The exploration of the means of representation and the inclusion of computational programs as generative tools might have an important role in the capacity to test and evaluate different design alternatives. Research relative to the impact of these tools allied to knowledge about the geometrical syntax of composition is necessary to the construction of consistent pedagogical strategies in design teaching specifically aimed at the students' cognitive development.

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