Improving Spatial Reasoning Through Drawing: How Shape Grammar Theory Can Unify Art and Geometry

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Introduction

The importance of shape grammars for developing spatial skills

Spatial reasoning and visual perception are necessary ingredients for scholastic success, especially in STEM subjects (Davis et al., 2015; Clements & Battista, 1992). However, there is much debate about how to improve these skills (Sarama & Clements, 2004, 2011; Davis et al., 2015). This research looks at how learning to visually calculate using shape grammars (Stiny, 2005) affects spatial skills and visual perception and asks: *how does* a drawing and design course using shape grammars improve these skills? This mixed methods research found that students in a 12-week drawing course (n=45) that put shape grammars at the core of the pedagogy (Stiny, 2005) significantly improved scores in the Beery Buktenica Visual Motor Integration Task, a culture-free, non-verbal test that measures visual motor integration and visual perception. Qualitative data also shows students' drawings and designs improved significantly. Participants moved from drawing a style of drawing I refer to as, *symbolic and language-based representations* toward engaging with *complex figurative visual-spatial calculations*.

Shape grammars are an algorithmic form of visual calculation, one that unifies artistic expression with a formal system of calculation (Stiny 2005). While shape grammars may not be a familiar concept, learning how to draw using shape rules is, in many ways, similar to learning linguistic grammars. Just as linguistic grammars are quintessential to learning how to calculate linguistically, which results in written language, shape grammars are quintessential to learning how to calculate visually, which results in visual language. Figure 1 is an example of a 1-rule shape grammar. The shape on the left is replaced by the shape on the right. The rule is applied recursively until the designer decides to stop, or change the rule.

Initially designed for generating paintings, shape grammars are currently used in post-secondary learning environments including: architecture, design, engineering, and computational design programs (Knight & Stiny, 2015; Martino, 2010; Strobbe et al., 2015).

This research moves shape grammar into another realm – K-12 education - and contends that learning how to visually calculate with shapes, spatial reasoning and visual spatial perception will improve precisely because of the emergent and generative process shape grammars initiate. While this research points qualitatively to an evolution towards complex figurative drawings, it also shows quantitative improvement in visual spatial skills and asserts that learning to draw and design figuratively with shape grammars is beneficial to improving visual art skills but also dynamically sets children up for algebraic and algorithmic thinking that is vital for learning in more abstract environments such as mathematics and technology. As can be seen in Figure 1, a shape grammar can be communicated algebraically using symbols (x) to represent a shape rule or can be communicated by drawing out the equation using shapes.

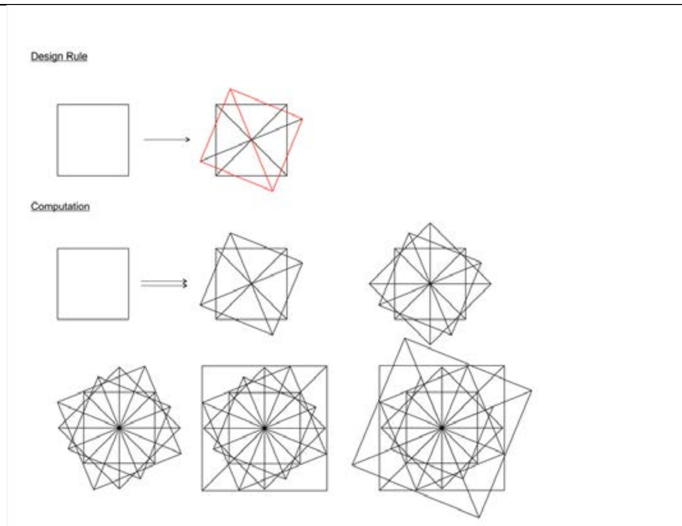


Figure 1. Shape grammar design based on the recursive application of the equation: $\mathcal{X} \Longrightarrow \mathcal{X} + (t)\, \mathcal{X}$ (Stiny, 2005)

Method

This research uses a “nested” (Morgan, 1998) mixed method design (Hesse-Biber & Leavy, 2011), in which quantitative testing is nested within a qualitative inquiry. Using pre/post testing and offering a 12-week observational drawing class, which used shape grammar theory my research was able to measure improvement in both the quantitative and qualitative data. Data was collected at four different sites in Montreal, Quebec, Canada: 1) A grade three class in a private school (n=17); 2) grade one, two and three students in a public school (n = 7); 3) a home school group of 6 to 9 years old (n=6); 4) a home school group of 10 to14 years old (n=9); 5) and a home studio group of 6 to 9 years old (n=5).

Quantitative Data Collection and Analysis

Quantitative data collection in the form of pre and post testing was used to assess students' Visual Motor Integration and visual perception skills. Visual Motor integration (VMI) was assessed using the Beery-Buktenica Developmental Test of Visual–Motor Integration (Beery VMI) —sixth edition. This test consists of 30 geometrical shapes that learners are asked to copy with a pen and paper. The test is terminated when three figures in a row have been incorrectly copied. The raw score is the total number of correct drawings that is then transformed to an age-corrected standard score. Research has shown a predictive correlation between VMI and a child's future academic performance in reading, writing, mathematics, and strong hand writing skills (Beery & Beery, 2010). The Beery VMI is a common screening tool used in Kindergarten and grade one classes to predict academic challenges early (Pfeiffer, B. et al., 2015).

Qualitative Data Collection and Analysis Methods

Data was collected through student portfolios and reflections. Each participant's work was analyzed and critiqued weekly using an analytic rubric. Themes and observations emerged, and were recorded. Observations and reflections were journaled after each session while the data was still fresh in the researcher's mind.

In terms of analysis, it is not easy to determine numerically how a student is doing and then rank them in accordance to their peers in Visual Arts. Using portfolio rubrics is one way that visual arts research can standardize how students' work is assessed, yet still allow for individual aesthetic interpretations of assignments. Analytic rubrics in visual art are designed to, "guide an assessor through a process that thoroughly scrutinizes an (art) object for evaluation" (Cavill, 2017, p.50).

Qualitatively I looked solely at shape grammars, asking questions that attempted to discern if the students grasped the idea of visual calculation, how they used it, and to what affect. The questions asked when looking over work each week included:

1) Can I see visual calculations in the work?
2) Did the student include shape grammars i.e. did they include one or more shape rules anywhere on their paper to give an indication of how they drew their picture?
3) Does the student's drawing recursively use shapes/shape rules?

Findings

Quantitative Findings

Table 1 illustrates the pre-post results for the Beery Buktenica Visual Motor Integration and Visual Perception Test for all participants. As the table illustrates, scores improved significantly and meaningfully. On average the students made large gains, increasing their scores by 10.78 points. A paired sample t-test reveals that students' gains were highly significant (Field 2011). The results also illustrate a large effect size.

Table 1 Pre-Post results on the Beery Buktenica Visual Motor Integration and Visual Perception Test (maximum score 130-)

Participants	Mean pre-test (SD)	Mean post-test (SD)	*T*	*P*	Effect Size
n=45	93.86 (10.54)	104.64 (10.75)	8.60	2.80E-11	1.01

Small effect size, $d = 0.2 – 0.3$; medium effect size, $d = 0.5$; large effect size, $d = 0.8$ (Cohen, 1988)

In Quebec, Canada, where this research took place, the education curriculum operates on a cycle system. In the first half of a Cycle, new concepts are introduced and taught, which are then reinforced the next year in the last half of the Cycle.

Table 2 illustrates the breakdown of pre-post results for the Beery VMI by Grade Cycle. What this breakdown illustrates is that the gains made pre and post testing appear to be fairly consistent across cycles, ranging from a low of 8.89 (Cycle One, Grades 1 and 2) to a high of 13 (Cycle Three, Grades 4 and 5). That said, this sample is heavily weighted in favor of Cycle 2. Although t-tests show that the results from each sample breakdown are significant, the results are much more highly significant for the larger sample size in Cycle 2. This is likely a product of the larger sample size. It will be interesting to see in future research that incorporates more participants in the other cycles, whether the significance will increase similarly. There was also one student from the home school group who was in kindergarten and is not included in the Cycle chart. This student's score increased by 9.

Table 2 Pre-Post results on the Beery Buktenica Visual Motor Integration and Visual Perception Test Cycles 1-4

Participants	Mean pre-test (SD)	Mean post-test (SD)	*T*	*P*	Effect Size
Cycle 1 (n=9)	96.44 (9.76)	105.33 (11.71)	2.76	0.01	0.82
Cycle 2 (n=26)	92.15 (11.68)	103.42 (12.03)	6.50	4.1001E-07	0.95
Cycle 3 (n=5)	90.2 (5.63)	103.2 (4.38)	3.44	0.01	2.5
Cycle 4 (n=4)	100.75 (4.19)	110.25 (1.5)	4.35	0.01	3.0

Small effect size, $d = 0.2 – 0.3$; medium effect size, $d = 0.5$; large effect size, $d = 0.8$ (Cohen, 1988)

Qualitative Findings

The major theme that emerged from the qualitative data is that participants moved from drawing mainly *symbolic and assumptive, language-based representations* towards engaging in *complex figurative visual-spatial calculations*. This section begins by briefly examining *how* these complex figurative visual-spatial calculations manifested.

Symbolic and language-based representations

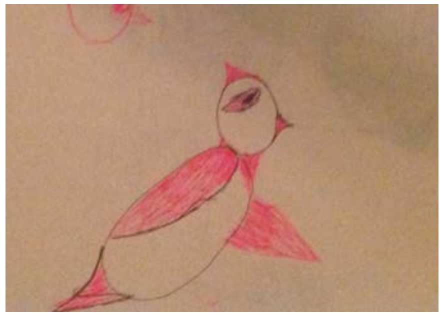
At the beginning of the class during the warm-up exercises, as can be seen in Figure 2, when students' were asked to 'draw a fishbowl full of things you like to draw' the results consisted of cartoon symbols and mediated images of animal-like, people-like characters and things. Few students *filled* their fish bowls. Most drew only one or two items, and many images were difficult to discern without an accompanied explanation. The drawings were 'symbolic' and 'assumptive'. They needed to explain what they were drawing using language, in order for their drawings to be comprehensible and make sense.

Figure 2. Class 1 Warm-up exercise, "Draw a fishbowl full of things you like to draw".

As can be seen in Figure 3, with very little instruction and working with shape grammar students start to try to draw more figuratively. I use less talking and rely more on *showing how* 'to look' before you draw. For instance, once they understood the importance of a bird's eye being aligned with the beak in order to hunt for food they started to put the eye in the correct spot in line with the bird's beak and tried to calculate with shapes to develop the body of the bird. Many students told me that this was the best drawing they had ever done. What they meant by this is that it looked the most like what they were trying to draw – a figurative representation of a bird.

Figure 3. Birds Week 2

Bird on tree – gr.1

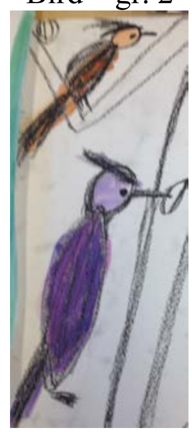


Bird – gr. 3

Bird – gr. 2

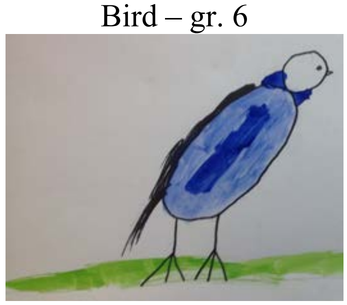
Bird - gr. 3

Bird – gr. 6



Bird – gr. 3

Bird – gr.3



Bird – gr. 3

Bird – gr. 4

Complex figurative visual-spatial calculations.

The birds in Figure 4 illustrate the trajectory most students took in the course. Students went from drawing naïve, simple symbols of birds to exploring visually various bird species: beak shape, habitat, colour, etc. The conversation accompanying the birds in Figure 4 vs the conversation accompanying the birds in Figure 3 was interesting. This change in classroom conversation (it became more grounded and focused on the task). It was significant across all sites.

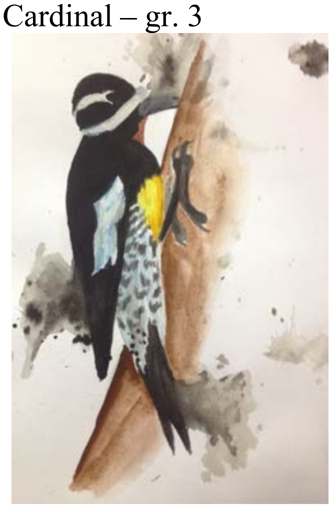
Figure 4. Birds Week 8.

Blue Jay – gr. 3

Cardinal – gr. 3

Cardinal – gr. 1

Canada warbler - gr. 3



Spotted Woodpecker – gr. 7

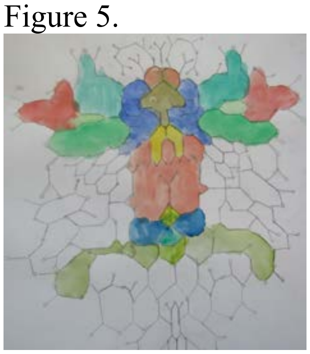
Yellow warbler with nest – gr. 2

Hummingbird – gr.4	Scrub Jay – gr. 6	RubyThroated Hummingbird – gr. 3

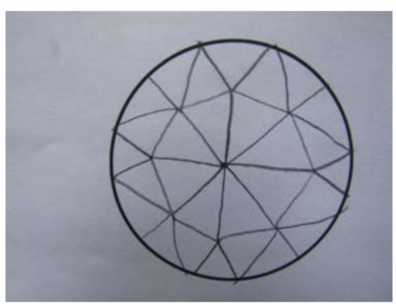
Using shape grammars to see and calculate

As can be seen in Figure 5, at four weeks in of instruction students were already starting to create complex figurative designs and, ultimately drawings using shape grammars. Learning how to create simple shape rules allowed students to embed shapes, merge them and use them recursively; this type of learning led to ever more complex compositions. Like linguistic grammars for writing, shape grammars are not didactic formulas rather they provide foundation from which to inquire, explore, and comprehend more. Unlike other subjects visual arts are taught similarly regardless of age (Walker, 2007). Age usually only means level of complexity of the work. It was interesting to observe the similarities in complexity of design between a student in grade 3 vs. a student in grade 6. In many ways the work was close if not equally complex.

Figure 5.

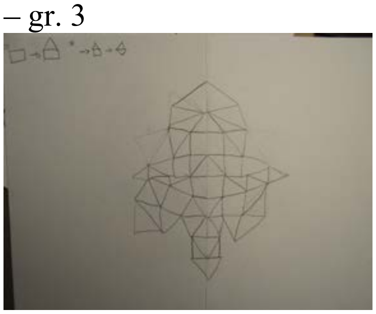


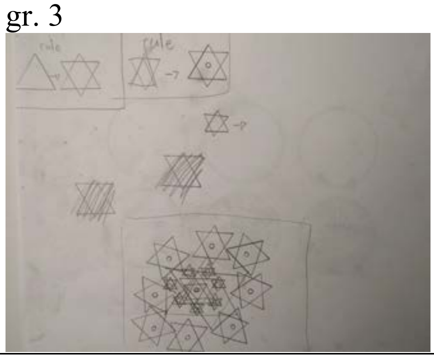
Branch grammar used recursively to create a bug – gr. 3

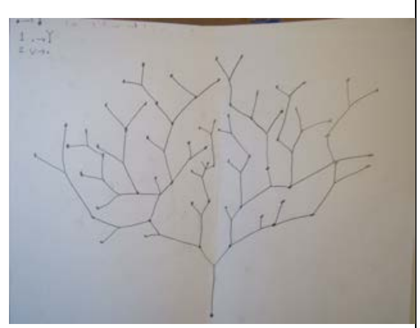


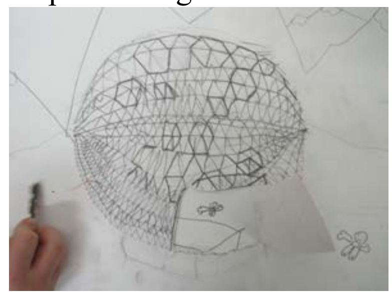
Branch grammar followed by a transformed triangle grammar – gr. 3

Branch grammar – gr. 3







Generating design with recursive use of grammars drawn in corner – gr. 3	Shape grammar: $\mathcal{X} \Longrightarrow \mathcal{X} + (t)\mathcal{X}$ used recursively – gr. 2	Branch grammar used to design the structure of a maple tree – gr. 3
		
Correctly drawn but misunderstood cube – gr.3	Geodesic Dome – gr. 3 using shape rule: $\mathcal{X} \Longrightarrow \mathcal{X} + (t)\mathcal{X}$	Geodesic Dome – gr. 2 using shape rule to draw over top of existing grammar: $\mathcal{X} \Longrightarrow \mathcal{X} + (t)\mathcal{X}$ with $\mathcal{X} \Longrightarrow \mathcal{X} + (s)\mathcal{X}$; $with\ \mathcal{X}$ being either a scaling hexagon or a cube.
		
Shape grammars used to calculate landscape with train – gr. 2	Branch grammar used recursively – gr. 7	Building up from a floorplan (floorplan lower left corner) – gr.6

Discussion

Teaching a rigorous drawing and design course that implemented shape grammars into the curriculum resulted in significant improvement in drawing and design ability. This qualitative finding corresponded with quantitative pre/post testing where significant improvement was measured in visual motor integration and visual perception. However, the standardized test falls short of truly measuring how learning to design with shape grammars improves spatial reasoning. The researcher is currently developing a tool that will adequately measure shape grammars and the effect of learning shape grammars on drawing/design. I hope to collaborate my research with research in mathematics and science, to teach the whole child (Upitis, 2011). Qualitatively, participants moved from drawing only *symbolic and assumptive, language-based representations* towards engaging in *complex figurative visual-spatial calculations*. This shift in vision by participants needs deeper analysis, as this research shows how improvement in spatial reasoning and visual perception is deeply rooted in visual art education that promotes technique first, which then leads to expression - not the other way around.

Introducing shape grammars into this course compelled students to try harder. Stiny (2005) argues the generative process whereby drawings and designs emerge by calculating with shapes is how shape grammars engage learners. My research confirms this. As the course went on and students began to realize that through easy steps complex images can be made, engagement increased. Precisely because shape grammars are simple to use they caught on especially well with students that previously struggled in the visual arts.

Limitations and Further Research

One limitation of this research is the sample size. A larger sample size with a control group should be the next step to further examine how drawing and design with shape grammars improves spatial reasoning and visual perception in learners.

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