

PRELIMINARY EXPERIMENTS WITH A HANDS-ON INTRODUCTION TO GENERATIVE DESIGN TECHNIQUES USING TANGIBLE OBJECTS

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Abstract

Generative Design (GD) is typically introduced to students through computer-aided design (CAD) courses. Diverging from this approach, this research uses hands-on experiments to introduce GD concepts to students. Shape Grammar (SG) and Cellular Automata (CA) techniques are explored using a tangible toolkit, distinct from CAD sessions. In an experimental setup, students use SG and CA techniques in separate sessions, following a think-aloud protocol. Data is captured using video recording. The study aims to uncover patterns in students' thought processes and assess if tangible exercises can instil confidence and interest in GD. The paper outlines the experimental setup, presents preliminary results, and discusses implications for teaching and GD tool development.

Introduction

Generative design (GD) is an iterative design process widely used in architecture to support human designers and help in design exploration. Various generative design techniques, including cellular automata (CA) (Herr & Ford, 2016; Von Neumann, J., 2017) shape grammar (SG) (Stiny, 1980), L-system (LS) (Lindenmayer, 1968), genetic algorithm (GA) (Jo & Gero, 1998) and swarm intelligence (SI) (Bonabeau et al., 1999) are reviewed based on preliminary literature review (Singh & Gu, 2012). In this paper, CA and SG have been introduced through tangible hands-on exercises.

Cellular automata (CA) is a collection of cells arranged in a grid of specified shape, and each cell changes state as a discrete time step, according to a set of rules depending on the state of neighbouring cells (Zaitsev, 2017). The essential components of CA are Cell, Cell States, and Neighborhood. Two kinds of cell neighbourhoods are usually considered in a 2D cellular automata theory. They are Von Neumann and Moore. Von Neumann's neighbourhood is considered in this work.



Fig. 1: Classical neighborhood in 2D CA a) von Neumann's neighborhood b) Moore's neighborhood (Zaitsev, 2017)

CA systems are widely considered in architectural design for their spatial abilities and form generation (Herr & Kvan, 2007; Krawczyk, 2002). CA produces unpredictable results after every iteration, which helps designers push their capabilities of creativity and imagination (Wolfram & Gad-el-Hak, 2003).

Shape grammar (SG) is a set of shape rules that can be applied to generate a set or language of design (Knight, 1999). According to Stiny (1980), the essential components of SG are a finite set of shapes, a finite set of rules, a finite set of symbols, and an initial shape. SGs are widely used to recreate architectural and design styles (Stiny & Mitchell, 1980; Poon & Maher, 1997; Stiny & Mitchell, 1998). The speciality of SG is to generate several design solutions using a finite number of shapes and rules. SG is widely used for design exploration and visual compositions (Tapia, 1999). The distinct feature of SGs is that they can be used as an analysis and synthesis tool to decompose complex shapes and generate complicated forms starting from a simple initial shape, respectively (Fasoulaki, 2008).

In this article, design experiments are performed with the help of a tangible kit relevant to solving the given problems using GD techniques. The design experiments assist in assessing and developing knowledge about the subjects' learning process and may provide a medium to support subjects' learning (Cobb et al., 2003).

Initially, the GD (CA & SG) technique is briefly discussed, followed by a background on related work. Then, the methodology is detailed, covering experiment design, subjects, data collection, and students' thought processes. Next, the experiment framework is outlined, including the problem description, constraints, rules, and setup details. Finally, results and discussions are presented, along with future work directions.

Related Work

Several studies have shown that incorporating GD techniques into design education can enhance the students' ability to explore design possibilities and improve their problem-solving skills (Fischer & Herr, 2001). These authors argue that design teaching should include more focus on techniques and skills in GD, especially in the initial stages of learning. Eris (2003) highlights the cognitive paradigm associated with the type of questions designers ask during the design process, which represents a convergent-thinking distinction. These studies also highlight the importance of hands-on experience in the learning process (Cassim, 2013). They present the findings from a case study of design students' reflections on their project experience. The reflections highlight the importance of hands-on experience with real-world problems in advancing a student's design knowledge and skills. Pusca et al. (2017) use case studies to show that hands-on activities can enhance students' knowledge and skills in design, creativity, communication, and modelling. They stress the importance of not only hands-on experiences but also minds-on to promote deeper thinking and understanding.

Junginger (2007) introduces the concept of "heart, hand and mind" as essential tools for design inquiry. However, most of these studies have focused on introducing GD through CAD systems (Krish, 2011 proposed a CAD-based design exploration method; Khan et al., 2019; Khan & Awan, 2018). CAD-based GD may not be accessible or appealing to all students initially because they need to learn to use the CAD tools and, perhaps, have adequate confidence in programming or coding scripts.

Hence, this research explores the effectiveness of incorporating hands-on exercises in teaching GD techniques, specifically using CA and SG. The goal is to determine if these tangible exercises can foster student interest and confidence in GD while improving their problem-solving and design exploration skills. The study also aims to analyse the students' thought processes during the exercises.

Numerous studies have explored the use of tangible tools for teaching computational and design thinking (Want et al., 2014; Lin et al., 2020; Matthee & Turpin, 2019). These studies highlight the benefits of using tangible tools in enhancing students' understanding of computational concepts and promoting hands-on learning. Soleimani et al. (2016) present a hands-on activity for the Computer Organization course in Computer Science using low-cost single-board computers. The results show that 90% of the students prefer hands-on activities to improve their learning and understanding of computational concepts. However, these studies have mostly focused on teaching programming concepts, not specifically GD. Marshall (2007) presents T-Maze, a tangible programming tool for children aged 5–9 to build computer programs in maze games by placing wooden blocks. Therefore, the current study aims to fill this gap by exploring the use of tangible exercises to teach GD techniques.

Research Methodology -

Experiment Design

The research on GD systems is often focused on reduced time and cost to achieve design alternatives, optimization, accuracy, consistency, and so on. Problem formulation and choice of the GD technique and representation play an equally important role, even if areas like optimisation steal the limelight. In this context, the experiment was designed to examine whether the tangible kit (discussed in a later section) can help students analyze the patterns in their thought processes while applying a GD technique to solve a given problem.

The experiments include three sub-experiments. Separate tangible kits are designed for each sub-experiment, as explained later in the framework section.

Subjects

The subjects for this experiment are postgraduate students in product design or undergraduates in architecture. Six subjects were selected, four from design and two from architecture. Although all the subjects have a background in design and architecture, they had yet to gain any knowledge of GD before this activity.

Experiment modules

The experiment sessions are divided into three modules. Each module has a demonstration video and reference manual explaining how to perform the activities. A moderator is still available during the experiment to clarify doubts (Toyong et al., 2020) and to ensure that the quality of recordings and data capture is acceptable. For reference, a demonstration video of rules and instructions is displayed on the screen throughout the activities.

Data Collection

Think-aloud protocol (Fonteyn et al., 1993) is used in the design sessions of approx. two hours, with approximately 10 minutes of break in between. The data is video recorded on tape, capturing both the verbal data and the evolution of the design through a camera directed towards the worktable with the tangible kit (Goldschmidt, 1994). A 10-minute post-session semi-structured interview was conducted with each subject, followed by open-ended feedback from the subjects about the whole experience. The interview (Patton, 1990) questions are outlined below

Interview Questionnaire (Semi-Structured)

- Which technique did you find easier to perform? Why?
- Any tangible thing or object you felt was missing from the experiment apparatus that'd have helped you during the experiment? Any suggestions?
- Which technique granted you more freedom while designing? Rank all three techniques.
- Did any part of the material or the experiment make you want to learn more about it?
- What part of the experiment did you find the easiest/clearest? What parts were unclear/more difficult?

Feedback Questionnaire

- What did you like about the experiment and its modules? What did you not like?
- How can we improve the delivery of content for better and easier understanding?
- Which content delivery method (manuals, videos, etc.) was most useful?
- Was there any ambiguity in any part of the experiment that halted your progress?
- Was the time allocated for reading manuals, watching videos and performing the experiment enough?
- Did you like the hands-on approach to learning Generative Design?

A five-point Likert scale, a standard measurement method in educational research (Boone & Boone, 2012), is used. A specific questionnaire for each activity is developed. Data is collected from the subjects at the end of the activity. Each question has a declarative statement that measures one trait, such as measuring the challenges associated with a specific technique. Numerically, the scale is assumed to vary from -2 to 2.

- The experiment has certainly helped me learn the Cellular Automata technique. (SA / A / NAND / D / SD)
- The experiment has certainly helped me learn the Shape Grammar technique. (SA / A / NAND / D / SD)

- *The experiments conducted today: Helped me learn more / Made no difference to how I learn / Were detrimental to my learning process*
- *The Cellular Automata module of the experiment is challenging. (SA | A | NAND | D | SD)*
- *I am comfortable with the activities performed in the Cellular Automata module. (SA | A | NAND | D | SD)*
- *The Shape Grammar module of the experiment is challenging. (SA | A | NAND | D | SD)*
- *I am comfortable with the activities performed in the Shape Grammar module. (SA | A | NAND | D | SD)*
- *The Tangible Free Design module of the experiment is challenging. (SA | A | NAND | D | SD)*
- *I am comfortable with the activities performed in the Tangible Free Design module. (SA | A | NAND | D | SD)*
- *I'd like to have such interactive exercises in my courses. (SA | A | NAND | D | SD)*

SA= Strongly Agree | A= Agree | NAND= Neither Agree Nor Disagree | D=Disagree | SD=Strongly Disagree

Data Analysis

The recorded data was transcribed (Tilley & Powick, 2002) and cleaned by an experienced transcriber. The transcribed data was subjected to thematic analysis (Maguire & Delahunt, 2017; Braun et al., 2016). Thematic analysis is an effective tool for identifying, analysing, and reporting patterns or themes within the data (Braun & Clarke, 2006). Two researchers independently conducted the thematic analysis for the whole transcript. The identified themes were reviewed again, and cross-checking against the transcription was done together. The questionnaire-survey results are analysed using descriptive statistics.

Experiment Framework

An exhibition layout problem was given for all three sub-experiments. The description of the problem is as follows.

“To design an exhibition space layout to display paintings such that there are four partitions/zones with similar spatial capacity. The paintings are displayed on stands such that there are an adequate number of surfaces to show the paintings. Adequate space must be provided inside the zones for visitors to walk and view the paintings. A 2D layout is expected (top view)”.

Requirements and constraints on the display stand:

A display stand combines flat panels as surfaces for hanging the paintings. A panel is represented by a tangible object (matchstick), and a display stand is essentially a set of multiple connected matchsticks. The viewing angle should be between 90 and 180 degrees. These panels are to be placed so that the two sides of the panel – front and back – are easily visible to the viewers.

Experiment type and description

This work involves three sub-experiments with respective kits. The details of each experiment are as follows:

Sub-experiment A: Free tangible (FT) without rules

There are no predefined rules and constraints. A free, unconstrained space made of cardboard is provided. Tangible objects, including matchsticks, clay, thread, and clips, are provided. There is no explicit connection or reference to GD for this part of the experiment. The free-form thinking of the students is captured. Figure 2 shows an example of the layout created by one of the subjects. -



Fig. 2: Display structure layouts designed by a subject for an exhibition hall with four zones.

Sub-experiment B: Cellular automata tangible (CAT)

This activity addresses the challenge of designing the display structures using a cellular automaton (CA) kit while considering structural rigidity constraints. The subjects are constrained to use no more than five panels to ensure stability, and a closed-loop structure is excluded due to ensure dual-sided visibility. A grid outline serves as the canvas for CA operations. The tangible kit employs matchsticks for creating display stands distributed in a 2*2 grid. Subjects engage in two sub-activities, focusing on display structure and layout planning. The goal is to assess the tangible kit's effectiveness in instilling fundamental computational thinking for GD while fostering confidence and interest. Decision-making is pivotal as subjects adhere to predefined rules, with their choices and justifications contributing to the learning outcomes.

CA rule formation and application –

CA usually uses a grid, and state changes are made according to the neighbourhood conditions driven by rules. The rule formation is discussed below:

Two cell states are considered for this activity, named A and B (Fig. 3). The state of the cells in the next iteration is governed by the state of the neighbouring cells in the previous iteration. Von Neumann's neighbourhood is considered for this activity.

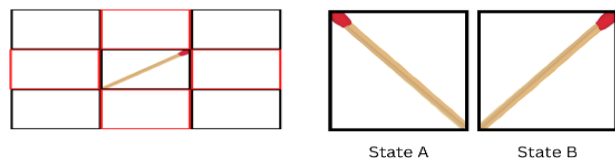


Fig. 3: Cell Von Neumann neighborhood

The following rules govern the cell state in the “New” iteration:

Rule #1: Assign cell state B if it has more neighbouring cells with state A; otherwise, assign cell state A if it has fewer neighbouring cells with state B.

Rule #2: If the number of neighbouring cells with state A is equal to the number of neighbouring cells with state B for some arbitrary cell position, then the cell state (in the "New" iteration) for that specific position is declared as:

Rule #2.1: State B (if the cell number of that arbitrary cell position is odd)

Rule #2.2: State A (if the cell number of that arbitrary cell position is even).

The three specified rules guide manual CA iterations. After three iterations, the subject evaluates the resulting display structures. Selection is based on logical assessment, requiring structures to maintain a continuous connection of panels (or matchsticks) without breaks for consideration. Figure 4 shows examples of some of the display structures generated by the subjects –

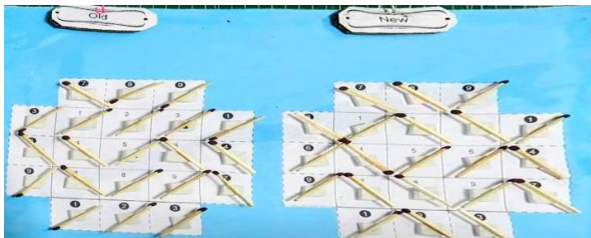


Fig. 4: Display structures obtained by a subject after performing an iteration of CA rules.

Once a display structure is selected, it is ready for arrangement in the four zones, marking the completion of the first part. Subsequently, three rules govern layout planning iterations, outlined below.

Arrangement of Tokens in the 4 Zones:

The chosen structures form four tokens through altered orientation and connection to a token's corner. Subjects can freely connect joints, ensuring the structure fits the grid. Design decisions and orientations must be explained, fostering robust decision-making. Figure 5 shows examples of tokens created by the subjects.

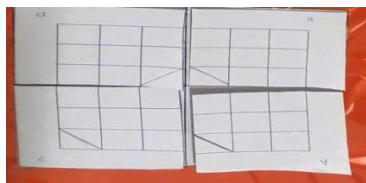


Fig. 5: Four tokens created by a subject.

Following token creation, these states represent CA, contingent on the subjects' creativity. A 2x2 grid, forming four exhibition zones, is generated for placing tokens A, B, C, and D. The grid has a computationally generated initial configuration, and tokens follow a 3x3 structure with walking space around the periphery, exemplified for exhibition formation. Figure 6 shows an example of a token configuration to form an exhibition-

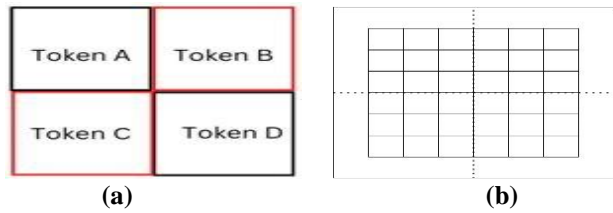


Fig. 6 (a) 2*2 grid for placing tokens (b) Tokens arranged to form an exhibition.

The newly created 2x2 matrix is used as the basis for the next set of 3 iterations in adherence to the set of grid rules given below:

Rule A: If token D neighbours either token C or B (or both) in the "Old" iteration, the token in the "New" iteration at that position will be token A.

Rule B: If token B neighbours either token A or D (or both) in the "Old" iteration, the token in the "New" iteration at that position will be token C.

Rule C: If token A neighbours either token C or token D (or both) in the "Old" iteration, the token in the "New" iteration at that position will be token B.

Rule D: If token C, with an odd cell label number, neighbours either token A or token B (or both) in the "Old" iteration, the token in the "New" iteration at that position will be token D.

Rule E: If token C, with an even cell label number, neighbours either token A or token B (or both) in the "Old" iteration, the token in the "New" iteration at that position will remain token C.

Default Rule: If none of the above rules are applicable, copy the "Old" state into the "New" state without any changes.

After performing three iterations, subjects have three different layouts and can use their decision-making skills and the requirement to select or reject a layout. Figure 7 shows an example of one complete layout made by one of the subjects.

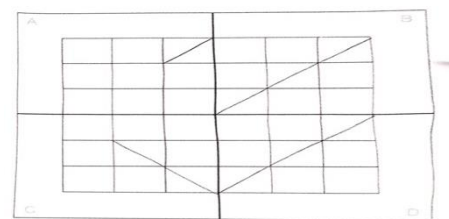


Fig. 7: A token layout obtained by a subject after performing the 3rd iteration on the 2x2 grid.

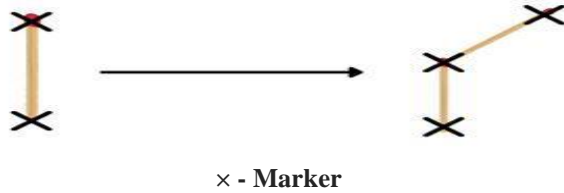
Sub-experiment C: Shape grammar tangible (SGT) –

SG has predefined shape rules, starting from the initial shape. This activity aims to analyze the subject's thinking pattern while applying this technique to solve a problem and whether the tangible SG kit can help subjects recognise the fundamental computational thinking approaches required in GD.

Two sets of rules are formed to perform this activity: the traditional SG rule to make geometric entities and the extension of SG called parametric SG (Angelo et al.,

2013) to make or play with the layout. Below are the rules for performing the SG activity –

Rule to Make Display Structure:



This rule is used to make display structures with the help of clay and matchsticks. There are two constraints that the designer should keep in mind when designing display structures:

- The angle between any two panels should be between 90 and 180 degrees.
- The number of panels should be less than or equal to five to handle structural rigidity.

Based on these constraints, a designer can make any number of display structures and name them entity 1, entity 2, entity 3 and so on. These entities will further help in parametric design rules. Figure 8 shows a few display structures made by subjects according to the above rule –



Fig 8. Display structures made by the subject

Rule to Design Exhibition Layout

A 10x10 grid with proper scaling and thread will be provided to the designer. The two parametric rules which will be used for the layout design are mentioned below-

Rule 1 –

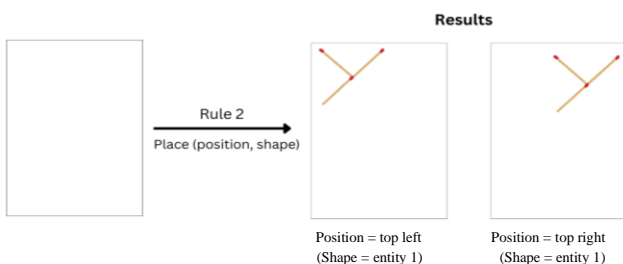
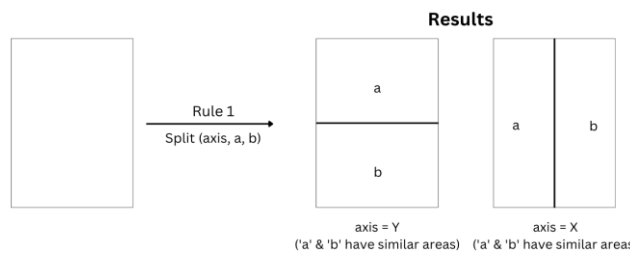


Figure 9 shows an example of the layout created by the subjects with the help of the given rule and objects-

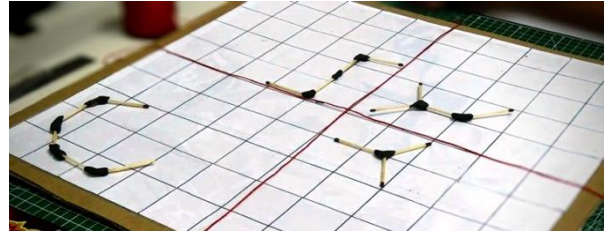


Fig. 9: Complete layout obtained using the SG rules

Table 1. summarizes the experimental setup.

S. No.	Experiment (E) Activities (A)	Timeline (minutes)		
		Sub experiment A-FTD	Sub experiment B – CAT	Sub experiment B – SGT
A)	Exp Handout	COMMON (5 MIN)		
B)	Video Briefing	✓ 2MIN	✓ 15MIN	✓ 5 MIN
C)	Doubt Session	✓ 5 MIN	✓ 5 MIN	✓ 5 MIN
D)	Ref Manual	✗	✓ 5 MIN	✓ 5 MIN
E)	Exp Activity	✓ 20 MIN	✓ 20 MIN	✓ 20 MIN
F)	Feedback	COMMON (10 MIN)		
G)	Questionnaires	COMMON (5 MIN)		

Result and Discussion

Four major themes emerged through thematic analysis of the transcribed data (Table 2). A detailed discussion of the themes is presented below –

User/Visitor Experience

This theme represents the importance of user flow in exhibition space layout. User flow is an essential aspect of spatial layout problems. Four out of six subjects spoke about the walking space arrangement of the panel, the field of view and the angle between panels (matchsticks), etc., to improve the visitor experience. For example, the experience of one subject is –

“Even if it is rigid 90 degrees, the corner space will not be well utilized. Here it provides a larger space for the people to have a standard view, and even the angle of view will be better. So, this will be straightforward, and there will be the utilization of space. If it is rigid 90 degrees, the corner will not be very convenient for the flow.”

– (Subject 4)

Here, the subject is describing the user flow along with the angle between panels when placing the display structure (entities in the case of SG) on free space.

Subjects’ Perception of the Problems

Although each activity involved enough supporting media and small doubt clarification sessions, each subject perceived the situation differently. The response of one subject is –

“Just want to clarify? So we may have to make four zones, right? Similarly spatial capacity!. So what do you mean by similar like? Is it like the number of displays should be the same for this one?”

– (Subject 1)

Response to GD Techniques

This theme includes and represents the intuitiveness while performing the GD technique. Almost all subjects spoke about the ease of applying CA and SG, the ease/difficulty of following the rules, constraints, and the freedom while designing the layout. How the computational thinking approach is recognised while applying the GD technique is also a part of this theme. Below is an example of the interview session –

“Interviewer - which technique did you find easier to perform and why?”

Subject 2 - If we talk in terms of performing, the last exercise was much easier because we have more options to do, I mean more things to do and with fewer complications, so we can just very freely work.”

This extract talked about intuitiveness in performing the GD technique. The subject found SG (the last exercise) easy to perform due to the freedom of design.

How the Kit Relates to Real-Life Problems

The tangible object and chosen problem statement make the whole experience like a real-life problem. Every subject visualized and tried to make the experience like designing an exhibition layout based on their understanding. Here is the experience of visualization of one subject while creating the layout plan –

“So this one is for having different and hear another theme. And similarly, this one like combines kind of these two, so one inclusive space kind and then have different themes on the outside”

– (Subject3)

Using codes for thematic analysis can help ensure consistency and rigour in the analysis process. By establishing a clear set of codes that define the themes of interest, the analysis can be more objective and less prone to bias. Combining codes to create broader themes can help synthesize the data and provide a more holistic understanding of the subject's thought processes.

A qualitative survey was collected from each subject based on the Likert scale to understand the subjects' experience and whether such a simple tangible exercise can generate confidence and interest in subjects' toward GD. The result of the study is presented in a graph (fig.10) below. The question is divided into three categories: FT design, CA, and SG. The responses of all six subjects based on the Likert scale (-2 to 2) are collected in three categories.

Table 2. Major Themes, along with a few associated Codes

Theme 1– User/Visitor Experience	Theme 2– Subjects Perception of the Problems.	Theme 3– Response to GD Techniques	Theme 4– How the Kit relates to Real Life Problem
Codes	Codes	Codes	Codes
Space for walking	Exploration of design space	Understanding of CA and SG rules	Geometry specific knowledge
Panel arrangement	Reinforcing problem objectives	Intuitiveness to perform	The relative size of the panel
Gallery theme experience	Doubt clarification	Design Freedom within and between techniques	Available zone space
Field of view	Constraint understanding	Computational thinking	Spatial Capacity
Angle arrangement between panels			

The incorporation of tangible kits into GD education has demonstrated positive outcomes in enhancing learning and comprehension. Subjects responded favourably to the tangible kit's effectiveness in teaching GD techniques, leading to improved understanding and comfort in applying each method. The kit facilitated the application of structured thinking, enabling subjects to explore a broader solution space—an essential aspect of GD. This hands-on approach allowed subjects to grasp computational thinking, offering insights not as apparent through traditional teaching methods.

However, challenges surfaced when subjects engaged in free-thinking activities, where the absence of constraints and ambiguity in design tasks led to negative responses. This suggests that open-ended design tasks requiring high levels of creativity and dealing with ambiguity can pose difficulties for some subjects. Despite these challenges, subjects did not express negativity regarding the comfort of performing each technique, highlighting the engaging and user-friendly nature of the designed experiment kit.

The study's findings emphasize subjects' positive responses to the tangible kit and its associated activities, particularly for understanding and comprehension. The contrast between activities with well-defined rules and constraints and the free-thinking task indicates subjects' potential struggles in open-ended design scenarios, suggesting the need for additional support to develop problem-solving skills in such contexts.

Subjects exhibited positive responses towards all the techniques in the kit, indicating their overall engagement and ease of use. This suggests that tangible exercises can be effective in teaching GD techniques and enhancing student engagement. Thematic analysis and code combinations were employed to delve deeper into subjects' thought processes, providing valuable insights for future design education practices.

The study's methodology, including subject selection and activity time allocation, was carefully considered based on a pilot study. The pilot aimed to refine tangible exercises, ensuring feasibility and effectiveness, addressing potential issues, and guiding adjustments to the experiment procedures. While the sample size may be perceived as small, it aligns with the study's focus on exploring tangible exercise effectiveness. The comprehensive exploration offered valuable insights for educators and designers considering hands-on learning in generative design teaching.

The inclusion of diverse subjects with varying design education levels and backgrounds enriched the study's perspective. The multi-session approach contributed to an in-depth understanding of subjects' experiences, enhancing the study's qualitative analysis.

This research's significance lies in its potential to elevate GD education. The study offers insights into improved student engagement with complex design concepts by assessing the effectiveness of tangible exercises in teaching CA and SG. Addressing a literature gap, it specifically focuses on tangible exercises for teaching GD, potentially influencing GD education and tools development.

In conclusion, this research advances GD practices and underscores the transformative impact of hands-on learning in design education.

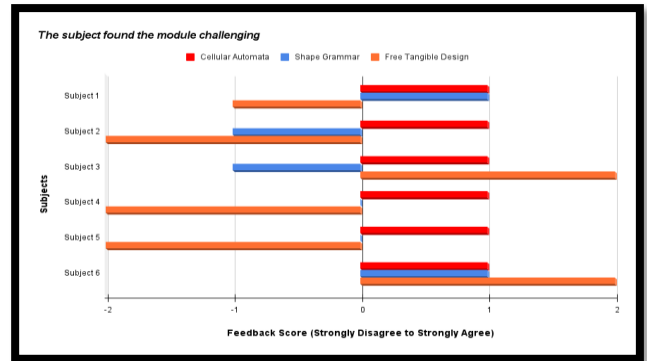
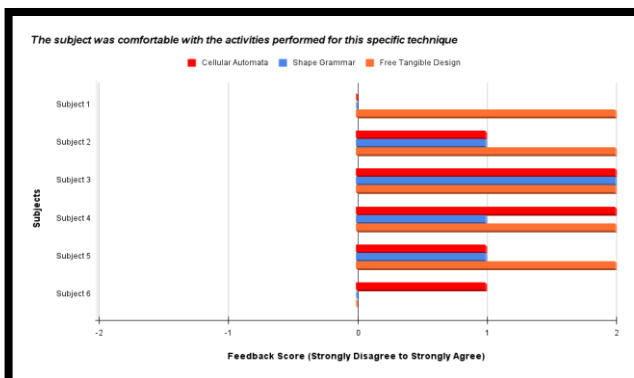
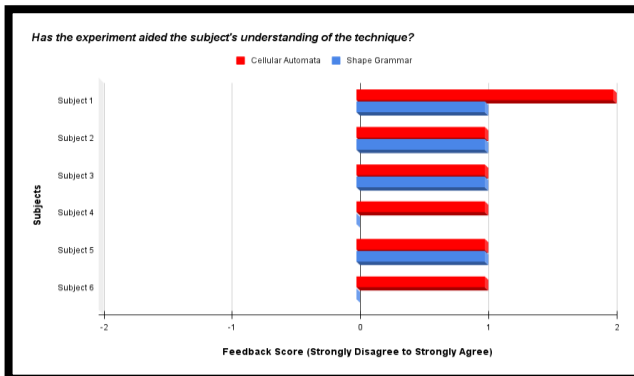


Fig.10 Results of subjects' responses based on the Likert data

Conclusion and future work –

Generative Design (GD) systems in architecture often employ various techniques, with two notable ones being Cellular Automata (CA) and Shape Grammar (SG). This study introduces tangible experiments using kits to enhance students' understanding of computational thinking in GD. The experiment aims to reveal cognitive processes and patterns in students' problem-solving approaches. Thematic analysis unveils insights into domain-specific knowledge and its role in design exploration. The findings underscore the importance of tangible exercises in fostering confidence and interest in GD, particularly in developing divergent thinking skills. The study acknowledges limitations, such as challenges in the free-thinking category, prompting the need for refined teaching methods balancing freedom and structure and the need for further experiments with more subjects having diverse backgrounds, which cover more diversity of student experiences and learning outcomes. Valuable insights into the effectiveness of tangible exercises using CA and SG emerge, suggesting potential extensions with additional GD techniques like L-system and Genetic Algorithm. Future work may include quantitative assessments of the experimental kit's efficacy and more detailed transcription analyses to identify computational thinking support. The future work could involve developing a taxonomy of knowledge based on the understanding of designers' and students' thought processes, identifying fundamental knowledge crucial in the generative design process. This research contributes significantly to design education, paving the way for future developments and exploration in the field.

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