TANGIBLE INTERACTION FOR PARAMETRIC DESIGN

by

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ABSTRACT

JINGOOG KIM. Tangible interaction for parametric design
(Under the direction of DR. MARY LOU MAHER)

Most research on tangible user interfaces for architectural design is undertaken from a technology perspective. While many studies focus on the development of new interactive systems employing tangible user interfaces for designers, there is a lack of study about the impact of tangible user interface on designers' perception (Mi Jeong Kim and Mary Lou Maher 2008). Moreover, most studies emphasize advantages of tangible user interfaces about modeling aspects, especially in terms of how tangible user interfaces can help designers to manipulate their modeling. However, recent advanced designs require parametric design with algorithmic process, and there is a lack of study on tangible user interfaces for algorithmic process. In this research I studied the effects of tangible user interfaces on parametric design supporting an algorithmic process in terms of learnability and design exploration. To highlight the expected effects of tangible user interfaces in learning environment, I compared designers using a tangible user interface on a tabletop system with cubes to designers using a graphical user interface on a desktop computer with a mouse and keyboard. The results clearly show that the use of tangible user interfaces influences on the ability of designers to learn parametric design. Specifically, the designers using tangible user interfaces engaged in more design exploration and discovered unexpected features. This research contributes to the understanding of how TUIs impact spatial composition. This type of tangible interaction has a wide range of applications in many other learning environments beyond architectural field.

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CHAPTER 1: INTRODUCTION

In this research I am studying the effects of TUIs on learnability and exploration of parametric design. TUIs can be easily and rapidly manipulated due to the physical nature of the artifacts. However, this brings to question whether such a physical interaction improves the ability of designers to learn and explore in a real design task. I believe that a more in depth understanding of the effects of TUIs on learnability and exploration can provide a new perspective unrelated to usability and is essential for the development of tabletop systems.

This research proposes that TUIs used for a tabletop system will affect several aspects of how parametric design can be learned and explored. Through the comparison of a design using a TUI vs. a GUI in a pilot study, I found some positive impacts of TUIs, the results of which are reported in this paper. The aim of this research is to empirically examine the ways in which designers perform parametric design using TUIs, in terms of learnability and exploration.

1.1 Constraints of Parametric Design

Although parametric modeling is a great approach in terms of offering automatic updates and creation, the existing parametric tools have quite a few constraints. These include unnecessary complexity with too much information, the problem of authorship, constrained creativity with a reactive Structure, learning difficulties, and collaboration. This research approaches two specific constraints related to tangible interaction.

The biggest challenge is allowing users more freedom in exploring design options. The existing parametric tools require user to follow very strict rules and paths; thus, the exploration of design options is very time consuming and is a burden in terms of recreating parts of a model. Because of this, the restrictions can be limiting. This constraint slows down the innovation process and can even force engineers to recreate parts of a model due to a failure.

A second constraint is the difficulty for users to learn or be trained. The strict rules of existing parametric tools require a lot of intelligence and too much information to work well in a design or model. The cognitive loads push users to remember a large amount of information in learning how to use each of the commands. A process such as this to make a script is an epistemic action rather than pragmatic action, and these aspects inhibit users' learning experience.

1.2 Potential Impacts of TUIs in Parametric Design

Most research on tangible user interfaces highlights the positive impacts and features of tangible interaction. Some studies demonstrate the cognitive aspects associated with creativity by physical action, while others focus on the learning effects achievable by tangible interaction. I believe that a current paradigm in the architectural field is how to develop a computational design process with parametric design. Through physical interactions, TUIs have the potential to solve this paradigm, since designers' activities for parametric design include spatial cognition.

1.3 Hypothesis

Based on the constraints of current parametric design tools as well as the potential impacts of TUIs, I hypothesized about users' perception with parametric design tool while using TUIs as follows;

Hypothesis: The affordances of TUIs can improve designers' learnability and exploration of parametric design.

The GUIs of current parametric tools are a kind of composition using elements for making node-based scripting. To make a composition for an algorithm, users first think about the whole making process and then go through the process step-by-step. These activities focus on the productivity of the design, rather than creativity and exploration. In other words, the burden of going back to the process makes the process an epistemic action rather than a pragmatic action. However, the use of TUIs with suitable tangible interaction can reduce this burden by using graspable user actions since the tangible composition provides immediate feedback. It is also easy to explore and manipulate the result of the composition. Moreover, such pragmatic actions encourage people to explore design options more freely. As a result, I argue that designers' physical actions through exploration affect their ability to learn.

CHAPTER 2: BACKGROUND

2.1 Tangible User Interfaces

Tangible interaction allows users to "grasp & manipulate" physical objects that embody digital information in the center of users' attention by serving as both a representation and a control of information. Fitzmaurice et al. (1996) introduced the term "graspable user interface" and Ishii and Ullmer (1997) coined the term "tangible user interface" (TUI). Tangible interfaces focus on the coupling of physical objects and digital information, thus eliminating the distinction between input and output devices. Fitzmaurice et al. (1995, 1996) present five basic defining properties that embody the graspable user interface concept: space-multiplexing of both input and output; concurrent access and manipulation of interface components; strong specific devices; spatially-aware computational devices; and spatial re-configurability of devices.

Many researchers studying tangible interaction highlight the positive impacts and features of tangible interaction. Specifically, multiple studies demonstrate the learning effects of tangible interaction, and others make claims about the cognitive and creative aspects. Moreover, some research presents the fundamental criteria for designing tangible interaction. These precedent studies provide related research fields, and my research topic which concerns the uses of tangible interaction in parametric design, is benefitted by the contributions of this research.

Mi Jeong Kim and Mary Lou Maher (2008) investigated the impact of tangible user interfaces on the spatial cognition of designers. In their study, they compared designers using a tangible user interface on a tabletop system with 3D blocks to designers using a graphical user interface on a desktop computer with a mouse and keyboard. They conclude that tangible user interfaces affects designers' spatial cognition, and these changes in spatial cognition are associated with creative design processes.

Paul Marshall (2007) examines the effects of tangible interfaces on learning. He provides an analytic framework of six perspectives, which can be used to motivate and guide work in cognitive science and education.

Eva and Jacob (2006) introduced parts of a design framework for collaboratively used tangible interaction systems. The systems can be interpreted as spaces/structures to act and move in, facilitating certain movements while hindering others. Thus, the shapes induce collaboration and provide both virtual and physical structure.

Mads Vedel et al. (2005) point out limited user actions in tangible user interface and provide fundamental characteristics of actions for providing a resource to designers of tangible interfaces.

Brygg Anders Ullmer (1997) provided a vehicle for moving beyond the keyboard, monitor, and pointer of current computer interfaces and towards the use of the physical world itself as a kind of computationally-augmented interface by presenting prototype applications on three platforms – the metaDESK, transBOARD, and ambientROOM.

Elise van den Hoven et al. (2007) observed a growing potential for a more design-oriented research approach and proposed several perspectives on tangible interaction.

Rahinah and Farzad Pour. (2010) drew a comparison between CAD and manual sketching tools. They discuss the identified advantages and challenges of current design media and then propose an alternative VR-based design interface for enhancing cognition and communication among designers during the conceptual design phase.

2.2 Parametric Design

Parametric design is a paradigm in design where the relationships between elements are used to manipulate and inform the design of complex geometries and structures. The term 'parametric' originates from mathematics (parametric equation) and refers to the use of certain parameters or variables that can be edited to manipulate or alter the end result of an equation or system. Parametric design is not a new concept and has always formed a part of architecture and design. The consideration of changing forces such as climate, setting, culture, and use is an essential part of the design process. (2014)

2.3 Tangible Interaction: Precedents for Architecture Design

There are many existing TUIs, and some of these attempt to deal with spatial design or parametric aspects by tangible interaction. I have selected several specific examples to emphasize the broad range of technologies and affordances in existing designs. The goal of this survey is to investigate how the special design and parametric components were manipulated and what kinds of interactions were used. The examples in this section are directly related to spatial design and they focus on the ways that specific factors can manipulate a model. Most studies in this field focus on modeling aspects. Even if they use tangible devices for 3D modeling, they focus only on manipulating modeling directly. Thus, there is no research about algorism approach using TUIs.

Taysheng Jeng and Chia-Hsun Lee (2003) introduced an interactive CAD platform that uses a tangible user interface to visualize and modify 3D geometry through the manipulation of physical artifacts. The tangible user interface attempts to reduce the apparent complexity of CAD user interfaces and to reduce the cognitive load on designers.

David Anderson et al. (2000) introduced a new approach to 3D modeling which uses construction toys. The tangible modeling system is a physical building block combined with graphical-interpretation. These physical building blocks self-describe, interpret, and decorate the structures into which they are assembled. They also provided a system for scanning, interpreting, and animating clay figures.

Dias, J.M.S. et al. (2002) presented a tangible, mixed-reality system for architectural design. The system provides the means for an architect to intuitively interact with an augmented version of a real scale model in normal working settings, where he can observe 3D virtual objects that are registered to the real ones.

The Triangles system is a physical/digital construction kit that allows users to use their own hands to grasp and manipulate complex digital information (Matthew G. et al. 1997, 1998). The kit consists of identical, flat, plastic triangles, each with a microprocessor inside as well as magnetic edge connectors. The Triangles system provides a physical embodiment of digital information as topography. The individual tiles are geometrically simplistic and therefore do not inherit the semantics of everyday physical objects.

2.4 Platform: Precedents for Tabletop with Sifteo Cubes

Sifteo cubes are tangible computing devices that have a digital display, sensors, and communication interfaces (https://en.wikipedia.org/wiki/Sifteo_cubes). Tangible interaction with the cubes is comprised of a variety of different actions such as press, shake, neighbor, and flip. These actions serve as the user input for the software running on the cubes. Each cube has its own display, which provides a visualization of digital content. However, the display size of the cubes limits the amount of content that can be presented to or controlled by the user. The small screen sizes also restrict the user from seeing the bigger picture, which is necessary when creating compositions.

The Samsung SUR40 with Microsoft PixelSense is a 40 inch multi-touch display (https://en.wikipedia.org/wiki/Microsoft_PixelSense). It enables experiences that change the way people collaborate and connect with a stunning 360-degree interface. The SUR40 sees and responds to touch and to real world objects, and is capable of supporting more than 50 simultaneous inputs. The device supports not only multi-touch and multi-user experience, but also object recognition. Object recognition refers to the device's ability to recognize the presence and orientation of tagged objects placed on top of it. Therefore, it can collaborate with other objects or devices for tangible interaction.

This section presents how the Sifteo cubes and tabletop is used and how they collaborate with other objects as a platform.

Most precedents using tangible devices utilize their own tangible devices that they developed. The usage of existing commercial tangible devices is meaningful in terms of universality and expandability. However, there is little research regarding the combination of tabletop with Sifteo cubes. Most studies use only tabletop or only Sifteo cubes.

Satellite is a collaborative musical table that uses both Sifteo cubes and Microsoft tabletop (http://www.sorob.com/#/satellite/). The users play with the Sifteo cubes, turning them into "satellites" that communicate with the main unit. The tabletop shows a planet that is surrounded by four satellites, each of which represents a musical track. Placing a cube in orbit claims the track. When the user presses the cube's screen, a note appears. Tilting the cube in different directions changes the pitch of the note. The music evolves over time, forming an ephemeral, ambient composition that varies from polyrhythm to soothing melody as the playhead sweeps across.

SynFlo is an interactive installation that utilizes tangible interaction to help illustrate core concepts of synthetic biology through outreach programs (Kimberly et al. 2012). This playful installation allows users to create useful virtual life forms from standardized genetic components, while at the same time exploring common synthetic biological concepts and techniques. The installation consists of Sifteo cubes that are used to modify virtual E. coli to serve as environmental biosensors. The modified bacteria can then be deployed into an environment represented by a tabletop computer, where they detect environmental toxins.

Nicolas (2011) presents a hybrid user interfaces that combine a 2D multi-touch tabletop display with a 3D head-tracked, transparent video. The interface is a modeling application and an urban visualization tool in which the information presented on the head-worn display supplements the information displayed on the tabletop through a variety of approaches to track the head-worn display relative to the tabletop. The tabletop supports create a 3D model using multi-touch and the head-worn display shows the real-time shape's change.

Nicole (2010) introduced a prototype for an interactive reservoir visualization system on Microsoft Surface. This system allows users to control reservoir models through multi-touch interaction.

Daniel (2011) presented an interactive LEGO application, which was developed according to an adaptation of building block metaphors and direct multi-touch manipulation. The application allows users to create 3D models on a tabletop surface.

Tangible Bots is a tangible tabletop interface that uses active, motorized objects (Esben Warming and Kasper 2011). Electronic musicians can use Tangible Bots to create music with a tangible tabletop application. Tangible Bots can reflect changes in the digital model and assist users by haptic feedback, by correcting errors, by multi-touch control, and by allowing efficient interaction with multiple objects.

CHAPTER 3: COMPARING GUI TO TUI

In order to highlight the expected effects of tangible interaction while using TUIs, I will compare designers in the following two settings: a tabletop design environment with TUIs and a desktop design environment with GUIs. The distinction between the two interfaces is the major variable in this study.

3.1 Experiment Design

The type of experimental design examines two conditions: between-subject design and usability. A Wizard of Oz (Kelley, J. F. 1983) experiment is conducted for the tabletop design environment. The tabletop and 3D cubes work individually thus the facilitator operates the tabletop interface according to the cube compositions of the participants.

3.1.1 Interfaces: 3D cubes vs. Mouse and Keyboard

3D cubes and a touch screen are used as the tangible input devices for the TUI and a mouse and keyboard as the input devices for the GUI in the experiments. The 3D cubes are manipulated from an existing digital tangible device called Sifteo Cubes and they include the same icons as the GUI interface. The 3D cubes are used to manipulate the algorithmic composition of components through the physical cubes' composition and the touch screen is used to manipulate variables such as width, height, angle, and number. Meanwhile, the mouse and keyboard use generalized interaction design, and these two general input devices act as a baseline against which the 3D cubes of the TUI can be compared.

Figure 1: A 3D cube (left), 3D cubes' composition (center), touch screen (right)

3.1.2 Affordances: 3D cubes vs. Mouse and Keyboard

While the desktop environment is hindered by the generalized affordances of the mouse and keyboard, the tabletop environment integrates the 3D cubes and tabletop into a joint cube-tabletop design. The 3D cubes and tabletop designs each have affordances, and these affordances can be described in terms of user actions and system actions. The affordances of the 3D cubes pertain to user actions on cubes and the resulting cube system actions, and tabletop affordances pertain to user actions on the tabletop display and the resulting tabletop system actions.

Figure 2: Tilt (left), press (center), neighbor (right)

Cube User Action	Illustrated User Action	Cube System Action
Tilt Left - Right		Move to next component (e.g. Ellipse, Grid, Copy)
Press		Select / Unselect current component
Neighbor		Connect components
Separate		Disconnect connection

Touch User Action	Illustrated User Action	Touch System Action
Drag		Change Variable (e.g. Copies, Scale, Rotate)
Spread		Zoom in (Window)
Pinch		Zoom out (Window)

Figure 3: TUI affordances

Table 1: Comparison of GUI affordances and TUI affordances

System Actions	GUI User Actions	TUI User Actions	
Find a Component	Click and Scroll Up/Down	Tilt Left - Right	Cube Affordances
Select a Component	Double Click	Press	
Deselect a Component	Click and Press Delete Button	Press	
Connect Components	Drag Line	Neighbor	
Disconnect Components	Click and Press Delete Button	Separate	
Change a Variable	Drag or Typing with Double Click	Drag	Tabletop Affordances
Provide Visualization	See Vertical Display (The Algorithm Window)	See Horizontal Display (The Algorithm Window or Connected Cubes)	
Zoom In	Scroll Up	Spread	
Zoom Out	Scroll Down	Pinch	

3.1.3 Systems: Tabletop vs. Desktop

The major differences between tabletop and desktop system are the display type and input system. An existing tabletop system called Microsoft Tabletop Surface is used for TUI, and its tabletop system consists of a large horizontal display with multi-touch input. The 3D cubes have their own display, and at the same time they can be used as the major input device for composition. The cubes can be used anywhere regardless of the location of the tabletop display, and the physical composition of cubes displays the algorithmic process on the cubes' own display. The desktop system is a typical desktop PC using a vertical monitor, a mouse, and a keyboard. The physical control space of the mouse and keyboard is separated from the output space by a vertical screen.

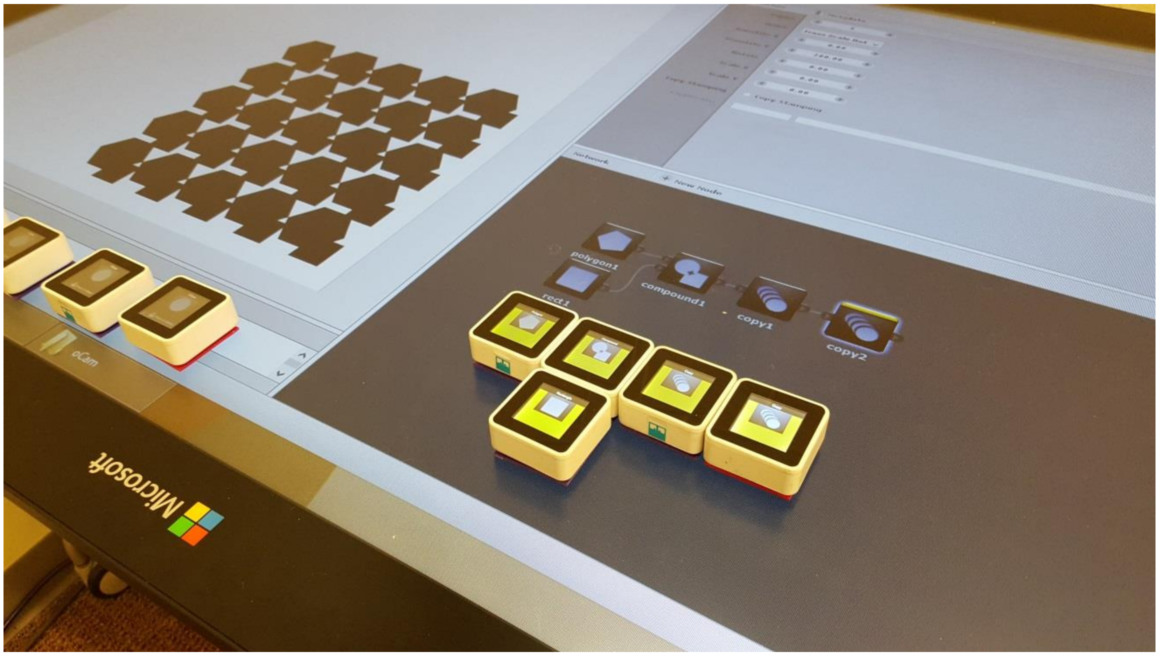

Figure 4: Tabletop system, 3D cubes

3.1.4 Application

Both the tabletop and desktop system use the same application, a pre-existing, free application called NodeBox (http://beta.nodebox.net/). Most popular parametric design tools such as Grasshopper (http://www.grasshopper3d.com/) use a node-based algorithm editor. Likewise, NodeBox is a simplified node-based software application that can create 2D visuals using Python programming code. NodeBox was chosen as suitable because it provides a simple interface and easy features. This is noteworthy since the existing parametric tools for architectural design are difficult to learn in a short period of time due to their complicated features.

NodeBox consists of four windows: the modeling, variable, coding, and algorithm space. The modeling window presents an output for algorithm composition with parameters according to the process of the algorithm and the variable windows. A model in the modeling window immediately reacts to changes in the parameters or algorithm.

However, users cannot modify the model directly in the modeling window without any altering the parameters or algorithm. Thus, the sole purpose of the modeling window is to provide a monitoring output of the current progress. The algorithm window is the most important part in creating a model since the basic structure of model is established by the relationship between components in the algorithm window. The menu of the algorithm window provides components as nodes, and users create components and then compose them to design the 2D visual. The connection method between components is similar to other existing parametric design tools that use component icons with line connections. Once users have created a component, they can modify specific parameters in the variable window. The variable window provides related parameters for each component, such as width, height, and color. This is different from existing parametric design tools due to the separated space from components. Lastly, the coding window presents the related Python code; however, the coding window is not used in this experiment.

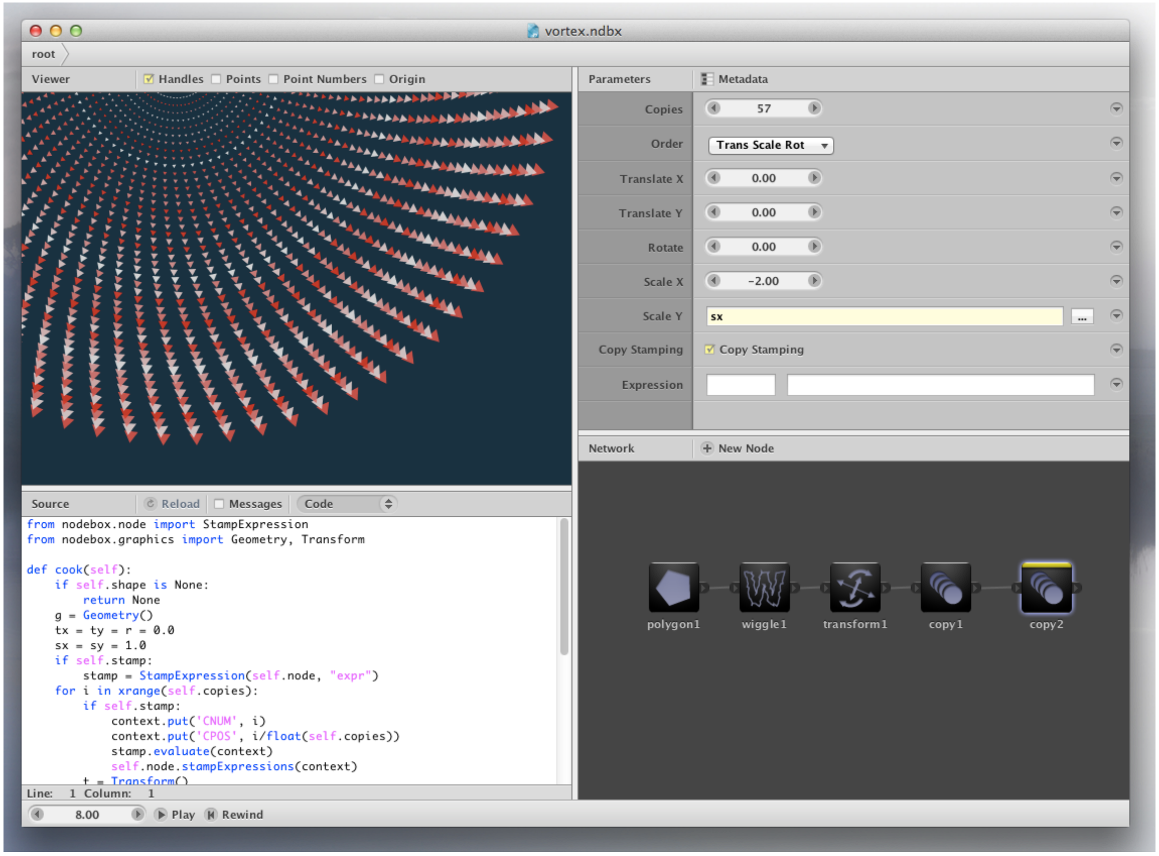

Figure 5: NodeBox

Although the NodeBox provides 41 components, 12 components were chosen for this experiment since it is not suitable to experience all components during this experiment. Therefore, the selected components consist of the necessary parts to create a basic geometrical pattern.

Table 2: Selected components

No.	Component Name	Description	Parameters
1	Ellipse	Create ellipses and circles	X, Y, Width, Height, Fill, Stroke, Stroke width
2	Rectangle	Create rectangles and rounded rectangles	X, Y, Width, Height, Roundness X, Roundness Y, Fill, Stroke, Stroke width
3	Polygon	Draw a polygon	X, Y, Radius, Sides, Align, Fill, Stroke, Stroke width
4	Star	Create a star shape	X, Y, Width, Points, Outer Diameter, Inner Diameter, Fill, Stroke, Stroke width
5	Copy	Create multiple copies of a shape	Copies, Order, Translate X, Translate Y, Rotate, Scale X, Scale Y, Copy Stamping
6	Compound	Add, subtract, or intersect geometry	Function, Fill, Stroke, Stroke Width
7	Place	Place shapes on points of a template	Copy Stamping
8	Reflect	Mirror and copy the geometry across an invisible axis	X, Y, Angle, Keep Original
9	Transform	Transform the location, rotation, and scale of a shape	Order, Translate X, Translate Y, Rotate, Scale X, Scale Y
10	Wiggle	Shift points by a random amount	Scope, Wiggle X, Wiggle Y, Seed
11	Grid	Create a grid of points	Width, Height, Rows, Columns, X, Y
12	Scatter	Generate points within the boundaries of a shape	Amount, Seed

3.1.5 Design Tasks

In order to identify the learnability and design exploration, two design tasks were developed to design 2D graphical patterns. During task 1, the participants experience the selected components while following facilitator's instruction and without any explanation of their features. Although the facilitator does not explain the components to the participants, task 1 covers all of the selected components' features in its instructions. The goal of task 1 is for users to understand the fundamental concepts and features of parametric design.

Table 3: Task 1 procedure

Category	Step	Instruction
Shape	1	Create Polygon
	2	Change Sides 6
	3	Create Rectangle
	4	Translate X 75, Y 75
Compound	5	Create Compound
	6	Connect Polygon (A)
	7	Connect Rectangle (B)
	8	Change Function (Difference, Intersection, Union)
Copy	9	Create Copy
	10	Connect Compound
	11	Change Variable (Copies 5, Translate X 200)
	12	Create Copy
	13	Connect Compound
	14	Change Variable (Copies 5, Translate Y 200)
	15	Create Copy
	16	Connect Compound
	17	Change Variable (Copies 3, Rotate 120)
Reflect	18	Delete Latest Copy
	19	Create Reflect
	20	Connect Copy
	21	Change Variable (Angle Random)
Scatter	22	Create Scatter
	23	Connect Reflect

Place	24	Create Ellipse
	25	Create Place
	26	Connect Scatter, Ellipse
	27	Change Scatter Variable (Amount Random)
Grid	28	Delete Copy, Reflect, Scatter, Ellipse, Place
	29	Create Grid
	30	Change Variable (Width 1800, Height 1800)
Place	31	Create Place
	32	Connect Compound
	33	Delete Compound and Rectangle
	34	Connect Polygon
Transform	35	Create Transform
	36	Connect Place
	37	Change Variable (All Variables Random)
Wiggle	38	Create Wiggle
	39	Connect Transform Change Variable (Random)

Task 2 is an open-end design task where the participants apply the components they learned from task 1 to their own designs. More specifically, the participants can create any design patterns using the selected components in 10 minutes. The goal of task 2 is for users to apply parametric features that they learned from task 1 as well as discover other features that task 1 does not cover through free exploration.

3.1.6 Participants

The eligibility criteria for recruiting participants is that the participant must be unfamiliar with existing parametric design tools in order to compare the two design environments and get consistent results, since using participants who are not familiar with parametric tools would lead to low variance in the experiment results. 20 participants who are 1st year architecture students are recruited from an architecture course. The experiment is a between-subject design; thus, 10 participants use the desktop environment and another 10 participants use the tabletop environment. Since 1^{st} year students are learning abstract geometrical patterns and are potential users for parametric design, they are suitable participants for this experiment. The students who will be recruited are asked a simple question before recruitment to determine if they meet the eligibility criteria.

3.2 Experiment Set-ups

The two experiment set-ups simulating tabletop and desktop design environments are installed in the same room. Each participant performs the same tasks with either the tabletop environment or the desktop environment.

3.2.1 TUI Environment

The tabletop environment includes a horizontal display, which is a multi-touch device called a tabletop, and ten cubes. The tabletop is running the NodeBox application for tangible parametric design, and the cubes are placed on the tabletop. A camera is used to record the participant's behavior and is installed where it can observe the participant's physical actions as well as the tabletop screen with the cubes' composition. Screen recording is used in order to create an analysis of the design process. To be specific, the screen recording data includes what kinds of icons the participants use, and how many designs and icons the participants create. Figure 6 shows the set-up for the TUI environment.

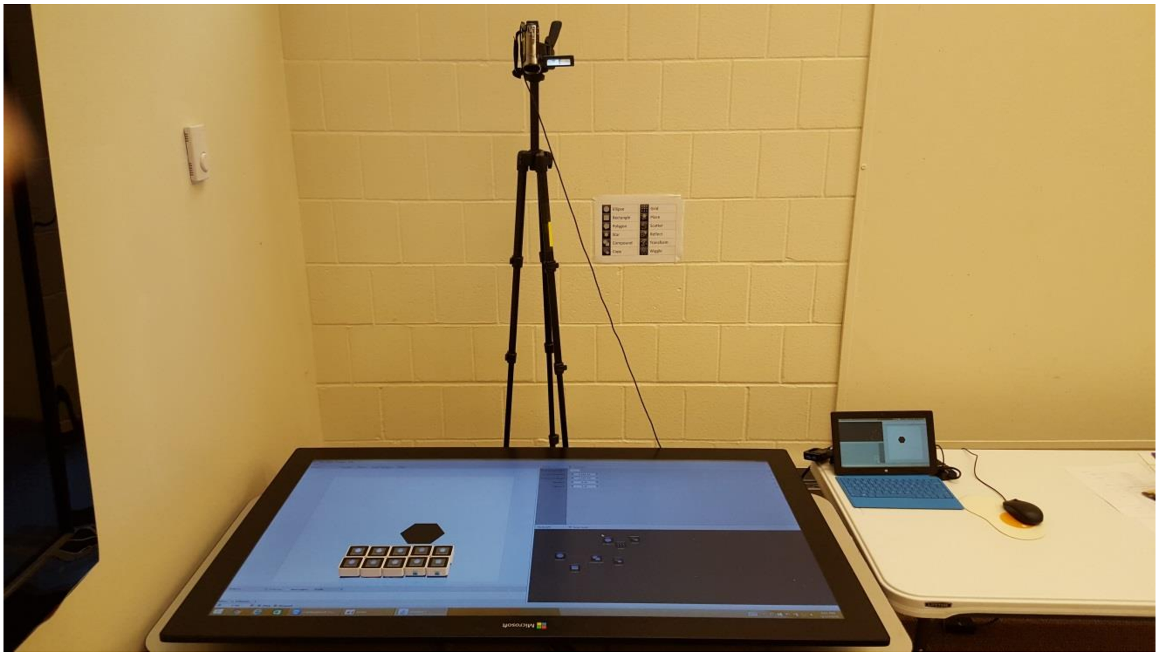

Figure 6: Experiment set-up for the TUI environment

3.2.2 GUI Environment

A typical computer configuration with a vertical screen, keyboard, and mouse is used in this environment, and it is similar to the normal desktop environment that the participants are familiar with. The overall experimental set-up, including the video and screen recording, is similar to that of the TUI environment. Figure 7 shows the set-up for the GUI environment.

Figure 7: Experiment set-up for the GUI environment

3.3 Experiment Procedure

The experiment procedure is as follows: training task, performing tasks, questionnaire, and interview. The participants are given some general information about experiment, and then they go through a training session before beginning the experiment. In the training session, the participants learn how to use the interface and device, what kinds of functions there are, and what the task they have to complete is. After the training session, the facilitator conducts the experiment with the two design tasks. Once the participants have finished the tasks, they are asked to fill out a questionnaire. Finally, the participants are interviewed after the questionnaire. This procedure is applied equally to the two conditions.

3.3.1 Training

The definitions and general features of parametric design are explained to the participants at the beginning of the training session. After that, they are instructed on how to use the Nodebox application, interface, and interaction model. To be specific, facilitator demonstrates how to use the windows and the menu, how to select and delete components, and how to change variables. Participants can test the application and device as a warm-up to make sure they understand how to use them if they want.

3.3.2 Experiment

Participants have two design tasks in this experiment and they receive an explanation about what they are doing and what they should be considering while performing the tasks prior to beginning the experiment. To be specific, they have to monitor the modeling window whenever they change a part of the algorithm window or variable window to understand a given component's role and its effects for each step following the instruction while performing the first task. Although the first task following instruction usually takes about 10 mins, the first task does not have a time limit, so they can have enough time to satisfy their understanding.

Table 4: Outline of the experiment

	TUI Environment	**GUI Environment**
Interface	3D Cubes and Touch Screen	Mouse and Keyboard
Hardware	Tabletop	Desktop with LED screen
Application	NodeBox	
Training / Design Task	10 mins / 20 mins	
Designer	Individual 1st year architecture student	
Design Tasks	Following instruction task and open-end task	

After completing the first task, participants begin the second task, which is the open-end design task. The participants have two limitations for the second task. The first limitation is the limitation of used components. They can use only the twelve components they learned from the first task, but may change any variable of the components, even if they did not learn some of the variables. This factor is a kind of discoverable feature that allows them to apply their understanding from the first task. Second, they have a time limitation of 10 minutes. They can produce any number of designs in these 10 minutes. To be specific, if they want to create a new design, they must delete all used components and then start the new design.

3.3.3 Questionnaire

The questionnaire consists of four categories: affordance and interaction, learnability and easiness, exploration, and engagement. To measure the quantitative data, each question has five-point Likert scale, and the results of Likert scale allow the TUI environment to be compared to the GUI environment.

In the first category, the participants are asked about used affordances and interactions. This category evaluates the suitability of the affordances of TUIs compared to those of GUIs that participants are familiar with. The questions in this category cover all used user actions and system actions, and each question asks about a subdivided affordance, such as tilt, press, or neighbor.

Affordance and Interaction

Seven items of the questionnaire addressed affordance and interaction:

Q1: It was easy to find a component.

Q2: It was easy to select a component.

Q3: It was easy to delete (or deselect) a component.

Q4: It was easy to connect components.

Q5: It was easy to disconnect components.

Q6: It was easy to change a variable.

Q7: I always keep track of my process easily.

Next, the participants are asked about learnability and easiness. Specifically, the first question in this category asks about participants' understanding while performing the tasks, and the second question asks about learnability of the user interface. The third question asks about the easiness of the user interface.

Learnability and Easiness

Three items of the questionnaire addressed learnability and easiness:

Q8: It was easy to understand how each component works and the relationships between components.

Q9: It was easy to learn parametric design.

Q10: I always knew how to perform a desired action.

In the third category, the questions ask about satisfaction with the user interface to evaluate exploration. The major part of exploration is to try various connections between components to create a composition of components; thus, the first question in this category deals with easiness of composition exploration. The second question deals with participants' frustration since their frustration can prevent the design exploration.

Exploration

Two items of the questionnaire addressed exploration:

Q11: It was easy to change a connected component.

Q12: I never felt frustrated from the interaction.

Lastly, engagement is measured as a part of exploration since engagement can encourage exploration. The first question in this category asks how enjoyable the interaction was, and the second question asks about encouragement to explore a creative design.

Engagement

Two items of the questionnaire addressed engagement:

Q13: It was enjoyable interaction.

Q14: It encouraged me to design creative graphic patterns.

3.3.4 Interview

The interview includes ten questions, which ask about learnability, exploration, and engagement. It consists of topics analogous to the questionnaire to get a specific reasoning about each topic. In order to gather the qualitative data that the questionnaire does not cover, the interview is conducted as a final session and the interview questions include those about specific difficulties, reasons, and understanding in terms of learnability.

Q1: You created an algorithm of graphical pattern during first task. The process includes creating shapes, changing variables, and making relationships. Were you able to learn and master all the features of the first task which you performed step by step? Tell me how much you understand as percentages.

Q2: Were any features or relationships difficult to understand during the first task (step by step)? If so, which features?

Q3: Was it easy to perform the second task (open-end task) using the features you learned from first task? Did you have any difficulties?

Q4: Were you able to discover any features that you did not use in the first task while performing the second task?

Q5: Was it easy to manipulate the process for exploration of various patterns while performing second task? If not, why?

Q6: Could you predict the cause and effect before actually changing a variable or connecting components? Why?

Q7: Was it enjoyable to learn parametric design? Why?

Q8: Was it easy to learn parametric design? Why?

Q9: Tell me about how to create this pattern (Show a pattern picture). You can draw the algorithm process.

Q10: Do you have any comments or suggestions about the parametric design experience?

CHAPTER 4: ANALYSIS AND RESULTS

There are three types of data collection for analyzing the experiment's results: observation, the questionnaire, and the interview. In order to get a sense of the overall tendency of the participants, each set of data has a different approach. First, the observation shows how many and what types of components and variables the participants attempted. This data represents the objective tendency of the participants' design process. Second, the questionnaire reports a subjective evaluation of the participants via self-reporting. Last, the interview presents details and descriptive information about the participants' experiences.

4.1 Overall Observations

The observation focuses on each participant's design process during task 2 (open-end design task) to finds trends in their progress since task 1 is to follow the instructions to learn basic features. I especially am observing how many components the participants try, how many variables they change, what kinds of components they use most often, and what unexpected features they discover in different design environments. The observations are measured in each design environment to compare the two different environments, which are the tabletop and desktop environments.

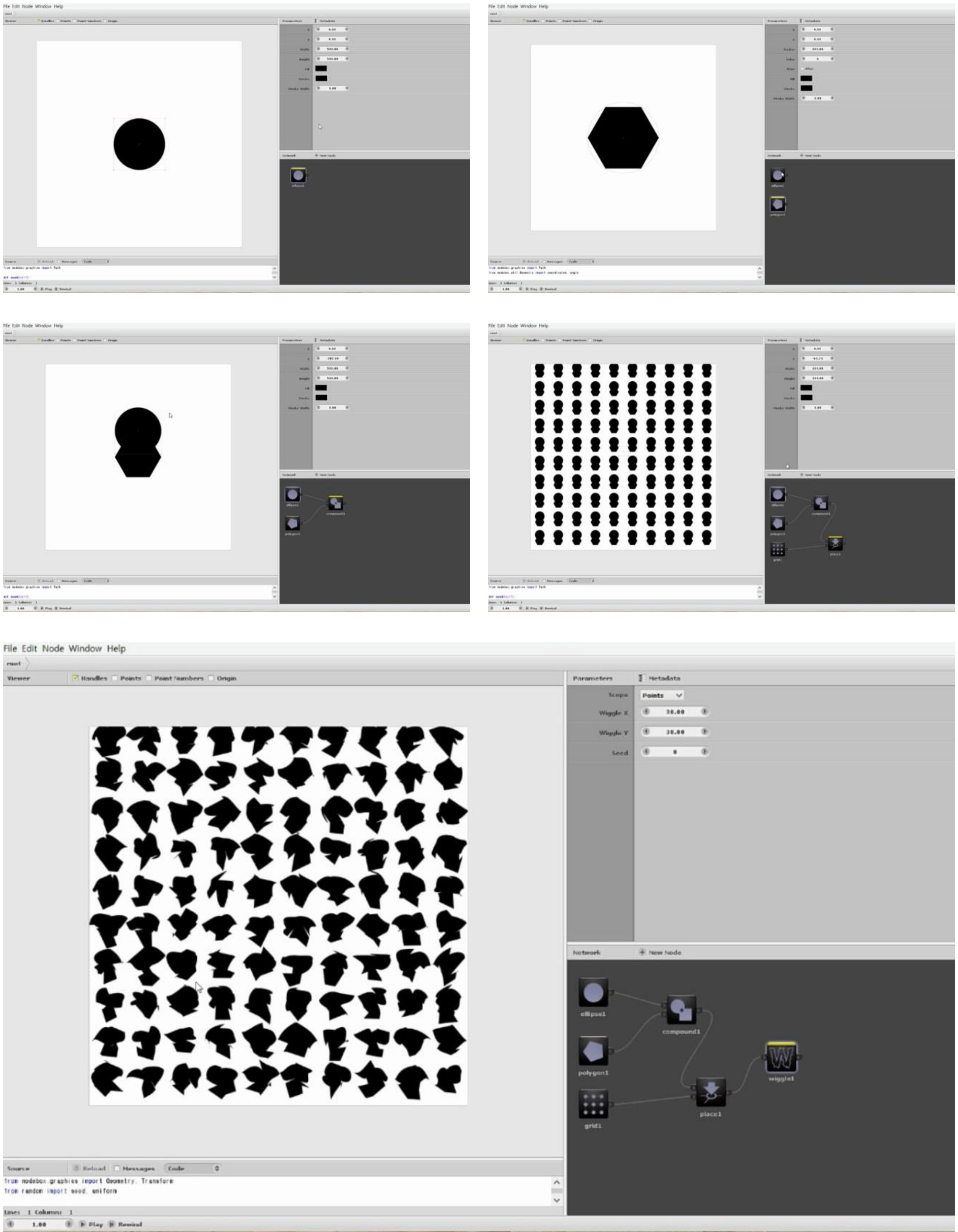

Figure 8: One of participant's progress

To measure the observation result, five metrics are used as follows;

1) The Number of Design Options (The Number of Algorisms)

The number of design options is the total number of algorisms that the participants produced during the limited time. The participants can produce any number of designs during their design progress. They can produce several designs or focus on only one design. The number of design options is measured in each design environment to compare the two different environments.

2) The Number of Attempted Components

The number of attempted components has two categories: the used components and deleted components. The number of attempted components is the sum of the two categories. The used components are the components in the algorism of the final design. On the other hand, deleted components are not used in the final design, but the participants tried these components during their process. When they create a design, they repeat to create and delete components. Thus, the number of attempted components, which is the total number of used and deleted components, reflects the amount of exploration during the participants' design process.

3) The Number of Variable Changes

Each component has several variables, such as X, Y, and Rotate, and these variables are another major factor to manipulate when manipulating a design using components. The number of variable changes is the how many times the participants change variables in their design process. This measurement shows a tendency, whereas the attempted components is presented as a ratio.

4) The Number of Discovered Unexpected Features

Neither the training task nor task 1 in the experiment procedure includes any additional features, so the discoverability of each environment while performing task 2 can be measured. The number of discovered unexpected features is the number of discovered features that the participants did not learn from the training task or task 1. In addition, the types of discovered unexpected features are evaluated to find a relationship between the discovered features and the design environments.

5) Attempted Component Types

The attempted component types are the components used and deleted among the 12 selected components for this experiment. The 12 components can be largely classified into two categories: Shape and Non-shape.

Basically, the results of the TUIs at each measurement are smaller than that of the GUIs since the tabletop environment used the Wizard of Oz method and the participants in the tabletop environment have a shorter design time due to operating time. In other words, the numerical results cannot be compared fairly. Therefore, the analysis of the observation results focuses on finding trends in differences considering this point.

I found some interesting points from the observation results, and the first major difference is the number of variable changes. Table 5 shows the results of three measurements: the number of designs, the number of attempted components, and the number of variable changes. The number of designs was similar in both environments, and most participants created only one design. As I mentioned above, the number of attempted components shows a big difference with almost twice as many attempted components in the GUI environment due to the Wizard of Oz factor. However, the number of attempted variable changes is not a great gap compared with the number of attempted components. Even the TUIs' percentage of variable changes per attempted components is higher than GUIs, and this means the TUI participants explored more variables for each component than GUI participants. This result is related to the affordances of TUIs using touch screen with tangible gestures, and it shows a potential possibility of TUIs in terms of design exploration.

Table 5: The number of attempted components and variable changes

	TUIs (Count)	**GUIs (Count)**
The Number of Design	**11**	**14**
Used Components	54	91
Deleted Components	41	59
Sub Total (Attempted Components)	**86**	**150**
The Number of Attempted Variable Changes	305	364
Total	**391**	**514**
Variable Changes / Attempted Components	**3.55**	**2.43**

Next, table 6 shows the result of discovered unexpected features. TUIs had a larger number of discovered features than GUIs, and this result is meaningful considering that TUIs had a smaller number of attempted components and variable changes. Multiple connections have large gaps while other features showed similar numbers. Multiple connections refers to a component that has more than two relationships with other components, and this feature is related to the neighboring of TUIs affordance. I assume that this characteristic of TUIs' making a physical composition with cubes is a discoverable feature rather than GUIs' affordance using a mouse with drag line since manipulating physical objects is an easy and natural interaction

Table 6: Discovered unexpected features

	TUIs (Count)	GUIs (Count)
Multiple Connections	5	1
Color	3	4
Stroke	2	3
Roundness	1	0
Total	**11**	**8**

Last, table 7 shows the number of each attempted component with each percentage. The largest difference is in the rate of attempted shape and non-shape components. The percentage of TUIs' shape components is 38.9% for used components and 29.3% for deleted components, and GUIs show 28.6% for used components and 20.7% for deleted components. The amount of used and deleted components for TUIs is about 10 percent higher than than that of GUIs. In other words, TUI participants preferred to explore shapes more than GUI participants, and this result seems to be related to the result of the variable changes explained above.

In addition, most common non-shape components of both environments are the same types, which are Copy and Compound. However, other non-shape components of TUIs show low percentages, which means that there is a high dependency on Copy and Compound, most likely because the participants preferred using familiar components to explore designs.

Another positive point is the use of the Place component. The Place component is the most difficult component to understand the concept of since it requires connecting two different types of components. Although GUIs used more Place components, TUIs showed a higher number of deleted Place components. This result can be interpreted as TUIs encouraging more exploration of a difficult feature than GUIs even if the participant does not understand the feature fully.

Table 7: Attempted component types

	TUIs				GUIs			
	Used		Deleted		Used		Deleted	
	Count	%	Count	%	Count	%	Count	%
Ellipse	5	9.3%	5	12.2%	4	4.4%	6	10.3%
Rectangle	5	9.3%	3	7.3%	4	4.4%	2	3.4%
Polygon	5	9.3%	1	2.4%	9	9.9%	3	5.2%
Star	6	11.1%	3	7.3%	9	9.9%	1	1.7%
Sub Total (Shape)	21	38.9%	12	29.3%	26	28.6%	12	20.7%
Copy	10	18.5%	4	9.8%	11	12.1%	6	10.3%
Compound	9	16.7%	4	9.8%	12	13.2%	5	8.6%
Place	2	3.7%	5	12.2%	6	6.6%	3	5.2%
Reflect	3	5.6%	3	7.3%	9	9.9%	3	5.2%
Transform	3	5.6%	1	2.4%	5	5.5%	3	5.2%
Wiggle	2	3.7%	2	4.9%	11	12.1%	2	3.4%
Grid	2	3.7%	7	17.1%	7	7.7%	13	22.4%
Scatter	2	3.7%	3	7.3%	4	4.4%	11	19.0%
Sub Total (Non-Shape)	33	61.1%	33	70.7%	65	71.4%	46	79.3%
Total	**54**	100%	**41**	100%	**91**	100%	**58**	100%

4.2 Questionnaire

The questionnaire consists of fourteen questions with a five-point Likert scale, and the results present the compared total score and score distributions for each question. Table 8 shows the total score of the participants comparing the TUI environment with the

GUI environment. Overall, the total scores of TUIs and GUIs are fairly close. However some questions show differences, and I highlight the score distributions with related factors in this chapter.

Table 8: Total score for the fourteen questions

	Affordance and Interaction							Learnability and Easiness			Exploration		Engagement	
	Easy to find…	**Easy to select…**	**Easy to delete…**	**Easy to connect…**	**Easy to disconnect…**	**Easy to change variable…**	**Keep track of my process…**	**Easy to understand…**	**Easy to learn…**	**Know how to perform…**	**Easy to change connected…**	**Never felt frustrated…**	**Enjoyable…**	**Encourage me to design…**
	Q 1	**Q 2**	**Q 3**	**Q 4**	**Q 5**	**Q 6**	**Q 7**	**Q 8**	**Q 9**	**Q 10**	**Q 11**	**Q 12**	**Q 13**	**Q 14**
TUI Total	44	43	48	47	47	37	33	26	33	28	39	35	47	44
GUI Total	45	42	48	38	42	39	35	33	38	28	33	38	46	45

First, the TUI total score for questions 4 and 5 is 47 points each, and these are much higher than the corresponding GUI scores of 38 and 42. Both questions 4 and 5 are related to neighboring of TUIs' affordance. To connect and disconnect components, TUIs use neighboring and separating cubes, while GUIs use dragging a line and deleting a line by selecting it. With equivalent results for questions 4 and 5, it seems that the neighboring of TUIs affordance has potential advantages. In addition, figures 9 and 10 show the distributions of questions 4 and 5, supporting the result mentioned above. While most TUI participants gave 5 points for both questions, GUI participants tended to report 4 points.

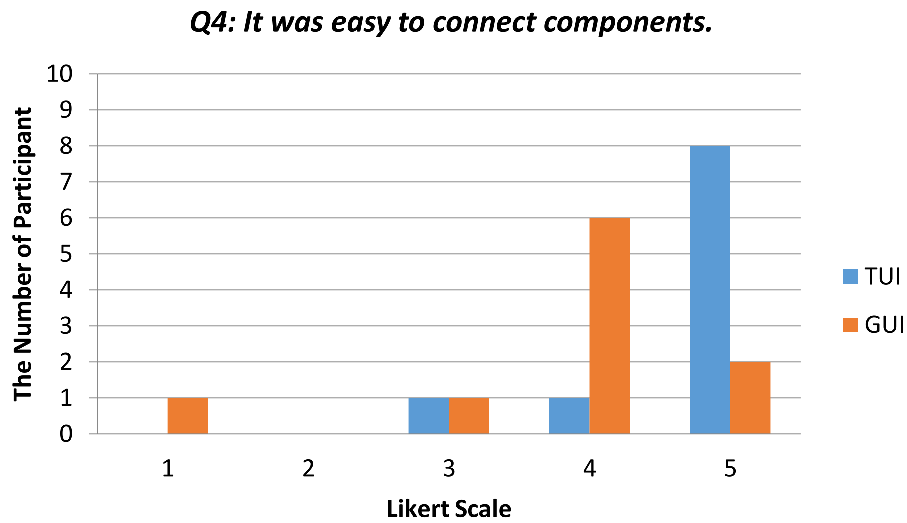

Figure 9: Q4. the number of participants for each Likert scale

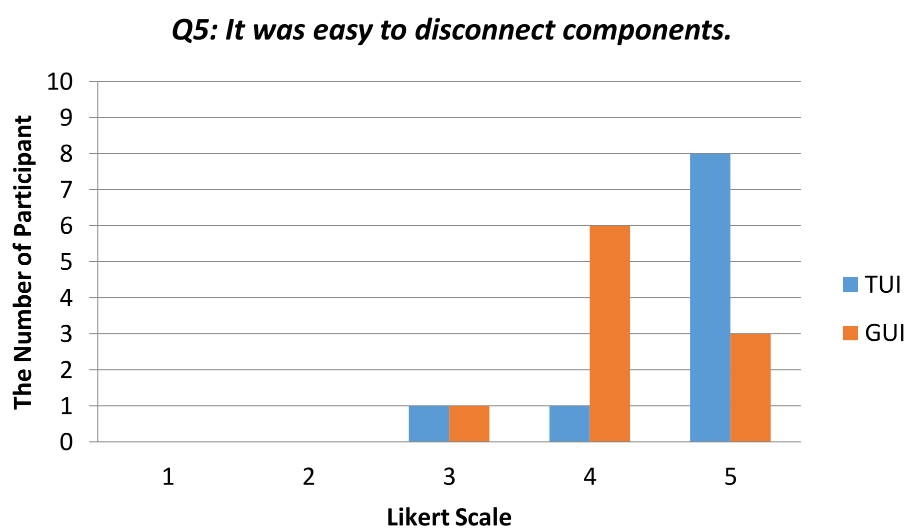

Figure 10: Q5. the number of participants for each Likert scale

Second, the TUI total score for the question 11 is 6 points higher at 39 points than GUI's 33 points, and this result reflects the potential explorability of TUIs since easy manipulation encourages users to explore more freely and reduces their frustration. Figure 11 shows the distributions of question 11 and it seems to be an opposite pattern.

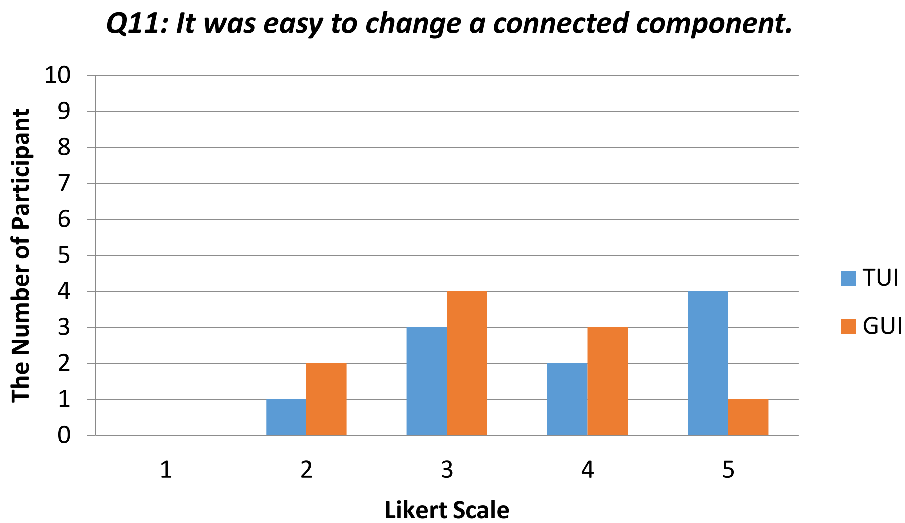

Figure 11: Q11. the number of participants for each Likert scale

Last, the results of question 12 show an interesting distribution. Although the GUI total score for question 12 is 3 points higher at 38 points than TUIs' 35 points, the distribution of the result put it in a different aspect. Figure 12 shows that the GUI score has an even distributions from 3 points to 5 points, whereas most TUI participants gave 4 points for the question 12. In other words, more participants of GUIs than TUIs felt frustrated from the interaction even if some participants of GUIs were more satisfied than those of TUIs. Frustration is an important factor influencing exploration in this point and it is interrelated with affordance and interaction. Therefore, this result reflects the satisfaction of TUIs' affordance and interaction as well.

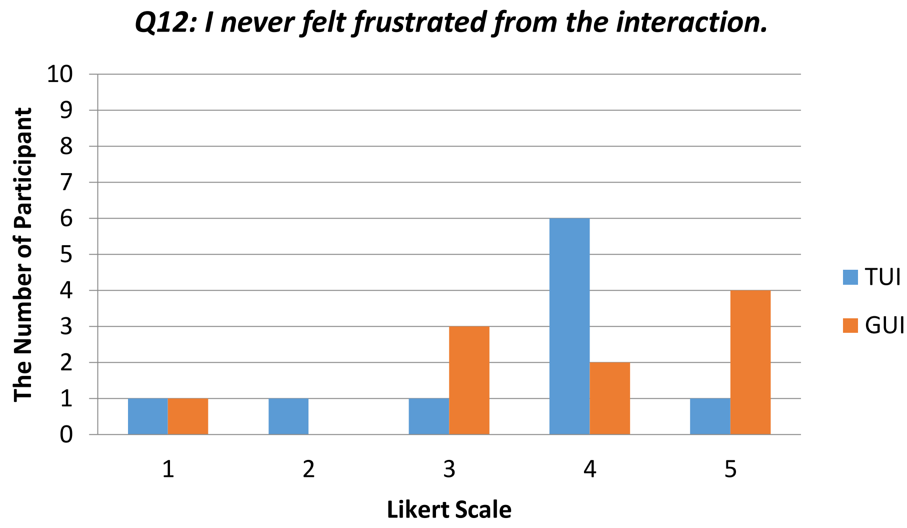

Figure 12: Q12. the number of participants for each Likert scale

4.3 Interview

The interview questions deal with learnability, exploration, and engagement. Overall, both the results of TUIs and GUIs showed that the participants experienced an analogous understanding level about parametric design, and the reasons they had difficulties were similar as well. Most differences between TUIs and GUIs were related to exploration, and I will describe the details in this chapter. The first question asks about overall understanding level of participants, and the average percentages of both environments were recorded at similar percentages. Table 9 shows the average percentages with each participant's percentages, and most participants of both environments were between 70% and 80%.

Q1: You created an algorithm of graphical pattern during the first task. The process includes creating shapes, changing variables, and making relationships. Were you able *to learn and master all features of the first task, which you performed step by step? Tell me how much you understand as percentages.*

Table 9: Question 1 result

	TUIs (%)	GUIs (%)
Participant 1	75%	-
Participant 2	75%	95%
Participant 3	85%	80%
Participant 4	60%	80%
Participant 5	80%	-
Participant 6	80%	80%
Participant 7	80%	50%
Participant 8	70%	75%
Participant 9	70%	60%
Participant 10	80%	70%
Average	**75.50%**	**73.75%**

The second question asks about specific difficulties, and the participants of both environments mentioned similar components, Place, Grid, Copy, and Compound, as most common difficult components. This result is the same as the result of observed component types, including low percentages of Place and Grid. In addition, some participants of both environments said that the most difficult feature was the connection concept and that it takes longer to understand.

Q2: Were there any features or relationships difficult to understand during the first task (step by step)? If so, which features?

Table 10: Question 2 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
No Difficulty	3	4
Component	3	2
Connection	3	4
Variable	1	0

The third question asks about specific difficulties with reason during the second task (open-end task), and most common difficulties were recall and understanding issues. In this case a "recall issue" means that the participants understand a concept or feature but do not recall how to use it, and an "understanding issue" means that they do not understand the concept or feature. Table 11 shows the result of question 3, with a similar number of recall and understanding issues for both environments.

Q3: Was it easy to perform the second task (open-end task) using the features you learned from first task? Did you have any difficulties?

Table 11: Question 3 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
No Difficulty	1	2
Recall	4	3
Understanding	5	5
Usability	1	0

Next, question 4 is about discoverability, and the result showed a significant difference. The eight participants of TUIs discovered some unexpected features that the participants did not learn from the first task, while only two participants of GUIs discovered some unexpected features. This result seems to correspond with the observation result that TUIs recorded more discovered unexpected features than GUIs.

Q4: Were you able to discover any features that you did not use in the first task while performing second task?

Table 12: Question 4 result-1

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
No Discovery	2	5

Table 13: Question 4 result-2

	TUIs (The Number of Discovered Features)	TUIs (The Number of Discovered Features)
Component	3	3
Connection	1	0
Variable	4	4
Total	8	7

Question 5 asks about exploration and table 14 shows the results and differences. The result says that the participants of TUIs had a less difficult with design exploration than GUIs, and this result seems to correspond to the questionnaire results indirectly in terms of exploration. In addition, some participants of TUIs mentioned the tangible aspects, whereas most participants of both environments mentioned the level of easiness and understanding issues. The participants who mentioned tangible aspects said that it was a fun experience for exploration even if they did not understand fully.

Q5: Was it easy to manipulate the process for exploration of various patterns while performing the second task? If not, why?

Table 14: Question 5 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
Easy	4	4
Somewhat	4	1
Difficult	1	5
Usability	1	0

Table 15 shows the results of question 6, which asks about predictability, and both environments presented similar results. Most participants of both environments could predict the effects of basic shapes such as polygon, but could not predict the effects of components with random features such as Scatter or difficult components such as Place or Copy.

Q6: Could you predict the cause and effect beforehand when changing a variable or connecting components? Why?

Table 15: Question 6 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
Most	2	4
Somewhat	6	3
Few	1	3
No Answer	1	0

Most participants of both environments answered for question 7 that it was enjoyable experience. However, some participants of TUIs emphasized the graspable interaction. They said it was extremely enjoyable with the new graspable interaction, while most participants of GUIs mentioned easiness and design aspects. Moreover, they wanted more time to explore and play with the cubes.

Q7: Was it enjoyable learning parametric design? Why?

Table 16: Question 7 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
Enjoyable	10	9
Not Enjoyable	0	1

Question 8 asks about overall learnability, and table 17 shows similar results for both environments. Most participants of both environments mentioned recall and understanding issues, a similar result to the results of question 3. They said that the basic concept was easy, but that it requires more time for clear understanding.

Q8: Was it easy to learn parametric design? Why?

Table 17: Question 8 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
Easy	6	6
Somewhat	3	1
Difficult	1	3

Question 9 is a type of quiz in which the participants imagine the process needed to create the design pattern shown, and the purpose of this question is to evaluate the learnability of the participants. There are two design patterns with different levels of difficulty for question 9. 9-1 of figure 13 is the easier pattern and 9-2 is the harder pattern. The participants of both environments drew the algorithmic process that they assumed was necessary after looking at each picture, and I counted the number of correct components in their process.

Q9: Tell me about how to create this pattern (Show a pattern picture). You can draw the algorithm process.

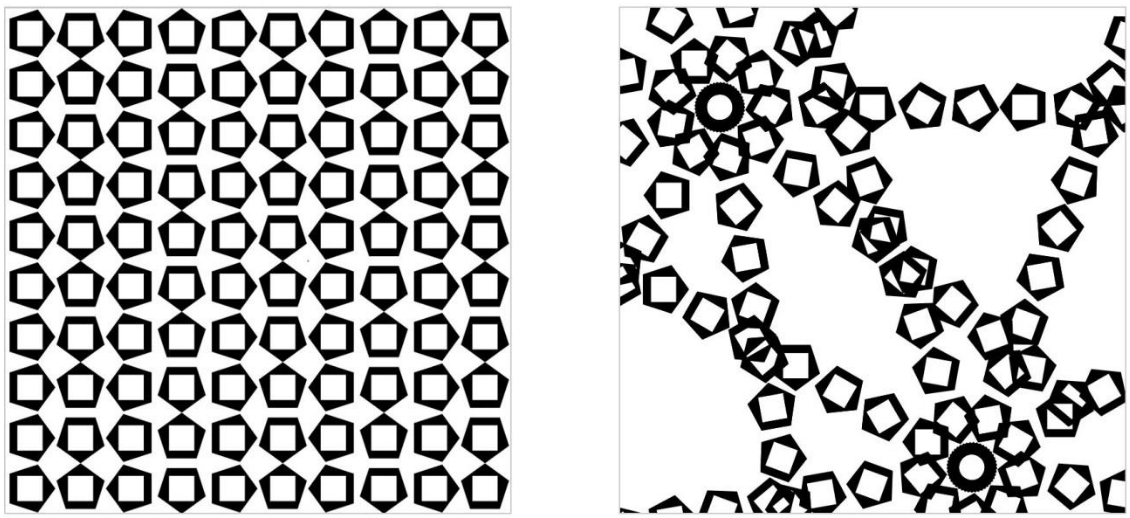

Figure 13: Interview question 9-1 (left), question 9-2 (right)

Table 18 shows the results of pattern 9-1, which is the easier pattern. TUI participants had more correct answers, a total of 42, than GUI participants, who had 38 correct numbers. Table 19 shows the results of pattern 9-2, and there is no difference between TUIs and GUIs.

Table 18: Question 9-1 result

	TUIs (The Number of Correct Components)	GUIs (The Number of Correct Components)
Participant 1	4	3
Participant 2	5	3
Participant 3	5	4
Participant 4	4	2

Participant 5	3	6
Participant 6	5	4
Participant 7	5	4
Participant 8	4	4
Participant 9	4	4
Participant 10	3	4
Total	**42**	**38**

Table 19: Question 9-2 result

	TUIs (The Number of Correct Components)	GUIs (The Number of Correct Components)
Participant 1	4	6
Participant 2	4	4
Participant 3	4	3
Participant 4	4	2
Participant 5	4	6
Participant 6	4	4
Participant 7	6	4
Participant 8	5	5
Participant 9	3	4
Participant 10	3	3
Total	**41**	**41**

Last, question 10 asks for suggestions about the parametric design experience that participants had during this experiment. Table 20 shows the number of comments per category. The biggest difference is that TUI participants were more concerned with interaction rather than interface, while GUI participants focused on interface. The TUI participants who commented about interaction suggested that the use of Swipe is better that the use of tilting for selecting a component.

Q10: Do you have any comments or suggestions about the parametric design experience?

Table 20: Question 5 result

	TUIs (The Number of Participants)	GUIs (The Number of Participants)
Interaction	3	0
Interface	0	3
Learnability	1	1
Usability	0	1

CHAPTER 5: CONCLUSION AND FUTURE WORK

This research presents the effects of tangible user interfaces on parametric design supporting an algorithmic process in terms of learnability and design exploration. To emphasize the expected impacts of tangible user interfaces on the learning environment, I compared designers using a tangible user interface on a tabletop system with cubes to designers using a graphical user interface on a desktop computer with a mouse and keyboard.

5.1 Conclusion

In this research I studied the effects of TUIs on the learnability and exploration of parametric design. This research proposes that TUIs on a tabletop system will positively affect certain aspects of the learnability and exploration of parametric design. Through the comparison of designs using a TUI vs. a GUI in a pilot study, I found some positive impacts of TUIs and will report the results of the experiment.

First, the results of experiment reveal that TUI affordances positively affected the exploration of participants. The observation results showed that the TUIs' percentage of variable changes per attempted components was higher than that of GUIs, which means that TUI participants explored more variables per component than GUI participants did. This result is related to the affordance of TUIs using touch screen with tangible gestures, and it shows the potential of TUIs in terms of design exploration. Moreover, the questionnaire and interview results related to exploration showed that TUIs provide more opportunities for exploring designs.

Next, the results of the observation and interview revealed analogous results in terms of TUIs' discoverability. Eight participants of TUIs discovered unexpected features, while only five participants of GUIs discovered unexpected features. The largest difference of discovered features was multiple connections, which is related to TUI affordances and physical characteristics. Thus, I assume that the physical composition of TUIs encourages users to discover unexpected features through more exploration.

As a result, the TUI environment showed some positive impacts for parametric design with improved design exploration and discoverability in this research. Although the results about learnability did not reveal a great difference, the advantage of TUIs providing more opportunities in design exploration and discoverability will influence learnability for parametric design.

5.2 Future Work

The biggest issue in this research is the usability issues of the used tangible user interface for the experiment. TUI environments implemented the Wizard of Oz method instead of a working prototype, and thus the participants of TUIs could not experience real TUI performances due to the delayed time for operating. Such a situation may affect their experience and experiment results. Moreover, some experiment data could not be compared fairly as well for that reason. In order to get accurate results, a further study needs to include a working prototype with full functions.

In addition, an interaction model for parametric design still needs to be developed, considering current users' mental model of using parametric design tools. The used application for this research is a simplified parametric design tool, and popular tools for architectural design such as Grasshopper use more complicated compositions of components. Moreover, some participants in this research suggested changing some user action. To support actual functionality of parametric design, future work needs to include an advanced interaction model.

I do not assume that the results of the experiment can be generalized due to the usability issue and the small number of subjects. Nevertheless, this research shows some positive possibilities of TUIs for parametric design by revealing the differences between TUIs and GUIs. Therefore, this research can be applied to other studies related with architectural design using TUIs, and to future studies.

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