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TIEboard: Developing Kids Geometric Thinking through Tangible User Interface

Keio University
Graduate School of Media Design

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A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

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Abstract of Master's Thesis of Academic Year 2022

TIEboard: Developing Kids Geometric Thinking through Tangible User Interface

Category: Design

Summary

In several educational setting manipulatives (such as Cuisenaire rods and Pattern blocks) play an essential part in children's learning, allowing them to explore mathematical and scientific ideas (such as number and shape) through direct manipulation of physical things.The aim of this paper is to take advantage of children's deep familiarity (and profound affection for) traditional toys by using them as a starting point.Simultaneously by seamlessly integrating computation within the tangible product that acts as both input and output device eliminating the need of traditional computers for any feedback or guidance.The aim is to create tangible interactive mathematical gadget to teach geometry that provide haptic feedback and appropriate hints when kids get stuck.The idea is inspired from traditional geoboards that are being used to explore geometry related concepts by creating, rotating and exploring different properties of shapes. The study focuses on the age group from 5 to 9 years old, starting from basic to complex shape learning.The main goal is to integrate technology into physical manipulative so kids do not have to look at the screen to know what they are doing, while making the activities more intuitive for kids to have more memorable learning experience.

Keywords:

Tangible user interfaces(TUI), Early education, Physical manipulatives, Tangible manipulatives, Interaction design

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Chapter 1
Introduction

In the turmoil of water, sand, and wind where the sea meets the land, life has flowered into a diversity of unique forms. We are now confronted with the challenge of reconciling our two citizenships in the physical and digital worlds on another shoreline between the land of atoms and the sea of bits. Our audiovisual sense organs are immersed in a sea of digital data, but our bodies are stuck in the real world. The digital world is only accessible through flat, square screens and pixels, or "painted bits." Unfortunately, one cannot feel or authenticate the virtual actuality of this digital information [3].

(Source Conference paper of Hiroo Ishii [3])

Figure 1.1 A Tangible User Interface is like an iceberg. *There is a portion of digital that emerges beyond the surface of the water into the physical realm.*

Consider an iceberg, a floating iceberg in the water. Tangible user interfaces are a metaphor for this. A Tangible user interface offers physical form to digital information and computation, extracting bits from the bottom of the ocean, bringing them to the surface, and allowing human hands to manipulate them directly [3](Figure 1.1). This Tangible user interface have a huge potential in early education for Kids. New computer interaction paradigms have made significant progress in this area, rethinking how physical toys can be utilized for both play and learning. These breakthroughs in computational and sensor technologies, commonly referred as 'tangible interfaces,' have had a significant impact on the field of educational technologies.Tangible interfaces allow users to engage with computers using real-world things that are relevant to the task rather than a keyboard or mouse [4].This section will **(1)** briefly introduce the deepening of relationship between Tangible user interfaces and learning of complex concepts for Kids, **(2)** state the problem this research is concerned about, **(3)** reveal personal motivation on the subject, **(4)** define the objective of the research.

1.1. Background

1.1.1 Learning with Manipulative Materials

Any kindergarten is likely to have a broad array of "manipulative materials." You might come across a set of Cuisenaire Rods, which are brightly colored wooden rods of varied lengths. The rods' colors and lengths are chosen with care to encourage children to explore arithmetic ideas and relationships [5]. As children develop and interact with these manipulative materials, they develop richer ways of thinking about mathematical concepts such as number, size, and shape.However, many abstract concepts are difficult (if not impossible) to investigate with standard manipulative materials. The notion that physical items may play an essential part in the learning process is a new approach. Formal education was nearly entirely based on lectures and recitations until the nineteenth century. Johann Heinrich Pestalozzi, a Swiss educator, was one of the first proponents of "hands-on learning" (1746-1827). Pestalozzi argued that kids should learn through their senses and physical activity, emphasizing the need of **"things before words, concrete before abstract [5]"**. Manipulative materials are now widely used in the classroom, particularly in the early grades.

1.1.2 Tangible Interfaces for Learning

TUI (tangible user interface) is a type of user interface in which a person interacts with digital data through their physical surroundings. The initial name was Graspable user interface, which no longer is used.TUI intends to seamlessly connect the digital and physical worlds, enabling people to gain knowledge of the world around them through holistic interactions with their surroundings.Human beings learn primarily through physical, cognitive, and emotional interactions with their surroundings.With the use of information technology, interactions have evolved beyond the limits of working on a desktop computer, using a mouse and keyboard to interact with windows, icons, menus, and pointers, while tangible user interface (TUI) is gaining popularity [6]. According to the research TUIs' aim to make computing genuinely ubiquitous and undetectable by linking digital information to ordinary physical objects and settings. In addition, Dourish proposed "embodiment" as the groundwork for a new fundamental approach called Tangible Computing in 1999, which emphasizes the material manifestation of the interface and the embedding of computational devices in the environment.Traditional computer-aided learning has been demonstrated in recent years to be influenced by innovative user interfaces, such as tangible ones [7].

Tangible Manipulatives for Learning Abstract Concepts

In particular, tangible objects have a long history in children's play and learning. Children can explore scientific and mathematical concepts such as number, form, and size using manipulative materials such as wooden blocks and jigsaw puzzles [8].Today, there is a significant presence of particularly designed educational toys known as STEM Toys that promote learning science, technology, engineering, and mathematics (STEM) through play, as research has indicated that TUIs have the ability to efficiently support activities that create meaningful and deeper learning in STEM. It has been demonstrated that a physical learning environment engages all senses and promotes overall child development since the kid receives direct feedback from TUIs while completing the activity. According to studies, TUIs' facilitate social interaction through collaborating, making collaboration an important skill in the increase of digital equity.Studies involving tangible engagement and children has centered mainly on how tangibles could promote or enhance learning or increase participation and engagement in learning [9].

1.2. The Problem

Research shows that collaborative learning and physical interaction with learning resources can significantly improve the student's comprehension of challenging mathematical concepts. It has been indicated in the research that geometry learning manipulative have been evolving ever since–such as pattern blocks, tangram puzzles to Computed Aided games [10] [11].These physical manipulates help children develop better understanding of challenging concepts by providing them with concrete representations. Moreover, it provides kids with the opportunity to explore the topic and learn collaboratively by being physically engaged in the learning process. Unfortunately, these manipulative do not provide any appropriate feedback to the kids to help in the learning process [12].The richness and interactivity of digital games is believed to enhance the learning experiences for kids.However, sitting in front of the screen, hearing through earphones, moving a mouse, tapping the screen, and clicking the keyboard have isolated kids from the physical world [13].Children have advanced their skills to perceive and manipulate their physical environments. However, when interacting in today's digital world majority of these skills are not utilized. There is a need to seamlessly link the digital and physical world that allows kids to have more interactive and memorable learning experiences [14].

1.2.1 Learning Geometry with Tangible Interface

The learning and advancement of mathematical knowledge and concepts is an important part of children's early academic development [15].

Research shows that despite the significance of geometry in later mathematics, it receives little teaching time and is confined to static geometry notions hence do not provide memorable learning experience to the kids [15]. Furthermore, many early childhood educators lack both topic understanding and confidence when it comes to teaching geometry [16]. TUIs increase knowledge of abstract concepts by interaction with physical manipulatives and embodied metaphors. By incorporating technology into everyday objects through natural acts such as grabbing, technology becomes omnipresent, integrating the physical and digital worlds.

1.3. Personal Motivation

We become what we behold . We shape our tools, and thereafter our tools shape us .—Marshall McLuhan[1]

Personally, I was always the enthusiast of new technologies. Since I was a kid, I have always been delighted with new technology advances.Nevertheless, I do also feel the downside of over using it especially with the computer or mobile screens. But personally I believe we can use the technology in the right way to keep the connection with the physical world around us. Also, being a product designer and having an experience in teaching, I was always interested to create innovative possibilities of learning with technology especially for kids.According to an old saying;*Give a man a hammer, and a whole world looks like a nail.*[2] Similarly,if we give a child with different manipulative they will tend to explore and learn new concepts.Like,when you give a kid pattern blocks, geometric relationships become more explicit [5]. However existing manipulative in kindergarten are not interactive and I always wanted to create something for kids that could have a two way of interaction.

1.4. Objective

The aim of this research is to take advantage of children's deep familiarity (and profound affection for) traditional toys by using them as a starting point. Simultaneously by seamlessly integrating computational abilities in the traditional learning toys to developing tangible manipulatives for kids to learn abstract concepts and enhance kids' learning experience.

1 He was a Canadian philosopher whose work is among the cornerstones of the study of media theory

2 This is a famous quote by Abraham Maslow which refers to a concept commonly known as the 'law of instrument' or Maslow's Hammer.

The objective of this research is to explore if kids shows an in depth understanding of geometric concepts when using tangible interactive product. We also want to learn that how kids learning experiences are effected with tangible manipulative having haptic feedback.I believe that this kind of exploration will help the future early education by providing teachers with tangible manipulatives to make kids learning more memorable.

1.5. Thesis Structure

Chapter 1

This briefly introduces the deepening of relationship between Tangible User Interfaces and learning of complex concepts for Kids,the problem this research addresses as well as the explanation of the research objective and my personal motivation.

Chapter 2

The literature review to deeply explain the Tangible User Interface in connection with learning for kids. This section will also focus on Geometric Learning in early education with traditional manipulative.Related works will then be discussed that mainly focuses on TUI's in education.

Chapter 3

A detailed explanation of the proposed solution "TIEboard" a tangible interactive medium inspired from traditional geoboard to teach geometry.

Chapter 4

An explanation of the research questions/hypothesis along with user study and evaluation.

Chapter 5

This section will explain the future work and conclusion of this research.

Chapter 2

Literature Review and Related Works

2.1. Early Mathematical Learning and Manipulatives

2.1.1 Early Mathematical Learning

Children in preschool and primary school have the potential to understand substantial mathematics, but most do not have the opportunity to do so [17]. Too many children not only fall behind their more privileged fellow students, but also begin a downward trajectory in mathematics.Interventions designed to help children learn mathematics in early education have a long-term positive impact on their lives. Mathematical reasoning is cognitively fundamental. Mathematics knowledge in preschool children predicts later school achievement in elementary and even high school. Furthermore, it anticipates later reading ability even better than early reading skills, and high school math study indicates college science achievement across subjects.Mathematics' quantitative, spatial, and logical reasoning abilities may serve as a cognitive foundation for thinking and learning across disciplines [18].Considering the significance of mathematics to academic achievement and a nation's economic success, all children need a solid foundation in mathematics from the start. Several research based interventions in the early education have been proved to be beneficial for kids learning. Some prominent examples in this category are *Pre-K mathematics [19], Building blocks for little kids [1] and Big math for little Kids [20]*.Mathematics interventions that are structured and research-based have been shown to be effective in supporting all children learn mathematics [18]. Kids develop an everyday mathematics that covers a wide range of topics (e.g., space, shape, pattern, number, and operations) and includes several important features as explained here: interest, concrete and abstract thinking, comprehension and misunderstandings [20]. Children already have many basic informal mathematical concepts on which teachers can base their instructions.

Geometric Learning

For early childhood domain of geometric is an important area of mathematical learning. Unfortunately,it is neglected in early years of education as most classrooms exhibit limited instructions on geometry,mainly because teachers are not confident to teach this domain or they believe that kids do not have knowledge in this as compared to numeracy [21]. Some mathematicians claim that, with the exception of simple calculation, geometric concepts underpin all mathematical thought [22]. Geometry can be used to bridge the gap between science and mathematics. Geometry was credited with the advancements of two of the most prominent physicists of the last century. Geometry should be emphasized at all ages, grades, and years. Mathematics curricula are more often criticized for their narrowness—'what does this have to do with the real world?' Geometry is the most important mathematical subject. It is central to physics, chemistry, biology, geology and geography, as well as art and architecture. It is also at the heart of mathematics, though the importance of geometry was obscured by fashionable abstraction for much of the twentieth century [22].

2.1.2 Manipulatives in Mathematical Learning

Math games that use manipulatives, puzzles, and physical activities have numerous advantages in the classroom. Firstly, they offer concrete understandings of abstract concepts, allowing more kids to understand them. Second, they allow children to investigate and assess their knowledge of math concepts. Third, they allow groups of kids to collaborate, discuss the issue at hand, and gain knowledge from one another. Fourth, they allow active young children to be physically engaged in their lessons rather than having to sit through a "boring" lesson or filling out workbooks [23]. A diverse collection of "manipulative materials" is likely to be found in any kindergarten. You might come across a set of Cuisenaire Rods, which are brightly colored wooden rods of varying lengths. The rods' colors and lengths are carefully selected to engage children in explorations of basic math concepts and relationships. Each brown rod is the same length as two purple rods—or four red rods.You might notice a collection of Pattern Blocks on the following table. Children can use these polygon-shaped tiles to make mosaic-like patterns while learning important geometric concepts [5].The NCTM [24] recommends the use of manipulatives in the classroom because it is supported by both learning theory and educational research. **"Manipulatives support learning by allowing students to progress from hands - on experiences to abstract reasoning."** Students take the first steps toward understanding math processes and procedures when they manipulate objects.*"The effective use of manipulatives can assist the students in connecting ideas and integrating their knowledge, resulting in a profound understanding of mathematical concepts."* When students use manipulatives and then have the opportunity to reflect on their experiences, not only is their mathematical learning enhanced, but their math anxiety is greatly reduced [25].

Figure 2.1 Traditional Manipulatives. *From Left to Right Cuisenaire Rods and Pattern Blocks.*

Manipulatives in Geometric Learning

The use of manipulatives, especially in geometry, can increase students' excitement and enjoyment. Manipulatives are a type of hands-on activity. Physical objects would be used to illustrate geometrical formations and relationships.Geoboards (See Figure2.2), cardboard pieces to demonstrate intersecting planes, and tangrams are examples of these kind of physical objects. Manipulatives' purpose would be to allow students to learn a geometric principle in more than one way. In other words, rather than just hearing about a mathematical principle, they get to see and feel it. Geometry and measurement concepts are best learned through hands-on interactions that involve experimenting and the exploration of relationships with real-world materials.Students are better able to apply their preliminary understandings in applied, real-world settings when they construct their own knowledge of geometry and measurement.Through explorations with real objects, they develop their spatial sense in two or three dimensions [26].

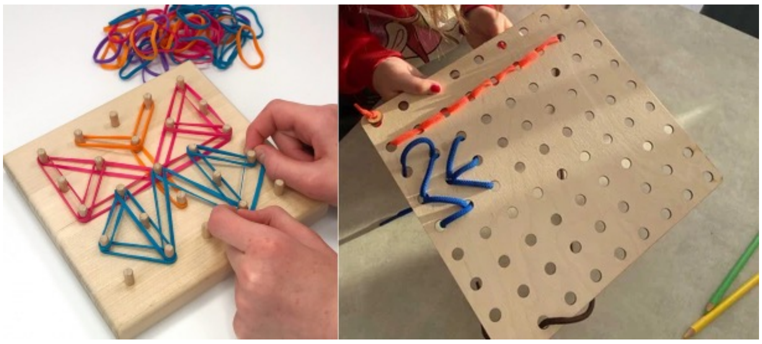


Figure 2.2 Geometric Manipulatives. *From Left to Right Simple Geoboard and Lacing Geobaord.*

2.1.3 The role of technology in Early Mathematical Development

The rapid development of technology in the twenty-first century has had a significant effect on children's learning models, methods, and forms. Children today are considered digital natives because they have been born and grew up in a technologically driven world [27]. Mobile phones, tablets, and computers are "gateways" into the digital world, but many of them are not always appropriate for children, particularly young children, because they are generally designed by adults and for adults. Thereby, the design and development of interactive technologies for children should take into account aspects of the child's development that affect their ability to learn and interact with the technology. In broad sense, Tangible user interfaces(TUIs) could be the best bridge between tangible form and digital information because they can clear the distinction between the two. As a result, TUIs are one of the most natural ways for children to interact with technology, particularly technology that supports learning [27].

2.2. Origins of Tangible User Interface

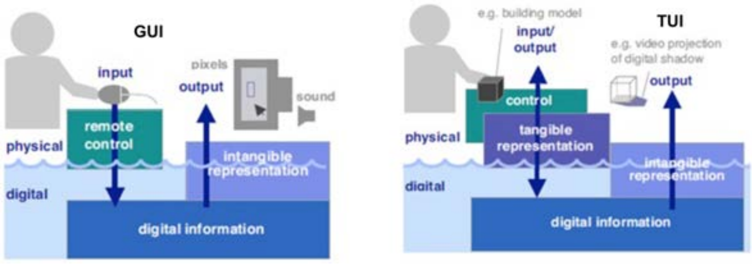
The fundamental inspiration for Augmented reality and ubiquitous computing is strongly linked to the development of the concept of a "physical interface."In 1993, a special edition of the ACM Communications titled "Back to the Real World" [28] suggested that both personal computers and virtual reality separate people from their "natural surroundings."The issue proposed that instead of compelling consumers to adopt a virtual world, they should enrich and enhance physical world with digital capability. This concept was driven by a desire to preserve the richness and situatedness of physical interaction, as well as an attempt to integrate computing in existing surroundings and human practices to allow seamless transitions between "the digital" and "the real" [29]. While the core concepts for tangible user interfaces were explored in the "Back to the Real World" special issue, it took a couple of years for these concepts to emerge into a distinct interaction style. Fitzmaurice et al. [30] proposed the concept of a Graspable Interface in 1995, in which graspable handles are being used to manipulate digital things. The more comprehensive idea of Tangible bits was offered by Ishii and his students [31] in 1997. Their aim was to transform the physical environment into an interface by connecting objects and surfaces with digital data.Based on this study, the tangible user interface has evolved as an unique interface and interaction design. Similar ideas were developed at the same time around the world, demonstrating an apparent need for a counter-movement to increased digitalization and virtualization. Suzuki and Kato created AlgoBlocks in Japan to assist groups of children learn to program [32].Logjam was created by Cohen et al. to help in video logging and coding [33]. For most of the decade that followed the introduction of TUIs as a revolutionary interface style, study concentrated on developing systems that investigated technical possibilities. In recent times, this proof-of-concept approach has given way to a more sophisticated stage of study, with a greater emphasis on conceptual design, user and field testing, critical reflection, theory, and the development of design knowledge.

2.2.1 Graspable User Interface

Fitzmaurice et al. [30] presented the graspable interface concept in 1995, which used wooden blocks as graspable handles to interact computer things.Their goal was to improve the usability and directness of graphical user interfaces.By placing a block on top of a graphical item on the monitor, it is anchored to it. Moving and rotating the block causes the graphic object to move in sync. When two blocks are placed on two corners of an item, a zoom is activated because the two corners are pulled along with the blocks. This enabled the two-handed or two-finger interactions that we now associate with multi-touch screens.

2.2.2 Tangible Bits

Hiroshi Ishii and his students introduced the concept of tangible bits only a few years later, which quickly led to the proposal of a tangible user interface [3].The goal was to make bits directly available and manipulable by employing the real environment as a display and medium for manipulation - the physical world would become an interface. Data could be linked to real artifacts and architectural surfaces, turning bits into tangible objects [31] [3].The switch from graspable to tangible appears to be intentional. Whereas "graspable" emphasizes the ability to manipulate objects manually, "tangible" encompasses "realness/sureness," the ability to be touched as well as the act of touching, and "GUIs fall short of embracing the richness of human senses and skills people have developed through a lifetime of interaction with the physical world." Using numerous senses and the multi-modality of human interactions with the real environment, we want to transform "painted bits" into "tangible bits"(Figure 2.3). We believe that incorporating graspable objects and ambient media into digital information would result in a far richer multi-sensory experience" [34] [3].



(Source Conference paper of Hiroo Ishii [3])

Figure 2.3 Difference between GUI and TUI. *TUI = Graspable objects + Ambient Media.*

2.2.3 Tangible Interfaces in Broader Contexts

(Source article of Shaer, Orit and Hornecker, Eva [34])

Figure 2.4 Research areas related to TUI's from left to right: *Tangible augmented reality,virtual objects(e.g airplane) are "attached" to physically manipulated objects (e.g card);tangible tabletop interaction,physical objects are manipulated upon a multi-touch surface;ambient Displays, physical objects are used as ambient displays;embodied user interfaces,physical devices are integrated with their digital content.*

Tangible Augmented Reality

Tangible augmented reality (tangible AR) integrate combine tangible input with an augmented reality display or output [35]. [34] Ex. augmented books, tangible tiles

Tangible Tabletop Interaction

Tangible tabletop interaction blends interactive multi-touch surfaces and TUI interaction techniques and technologies.This branch of study is beginning to look into the contrasts between pure touch-based interface and tangible handles [36]. Toolkit: reacTIVision, ex. Reactables

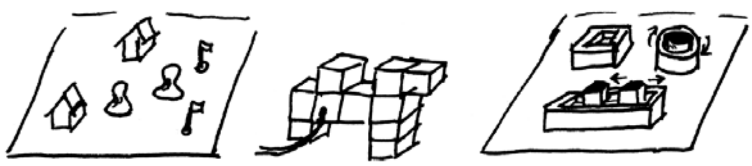
Ambient Displays

Ambient displays were originally part of Ishii's tangible bits vision, but they quickly grew into their own study area. According to Blackwell, tangible objects can shift between the focus and periphery of a user's attention, and therefore provide an example of peripheral (and thus ambient) engagement with tangibles [3].

Embodied User Interface

Embodied user interfaces recognize that computation is becoming increasingly integrated and embodied in physical products and appliances.Manual engagement with a device can thus become an important aspect of using an integrated physical–virtual device, with the device's body serving as the interface [37].

2.2.4 Types of TUI



(Source article Types of TUI- Ullmer and Ishii, 2005 [38])

Figure 2.5 The three dominant types of TUIs:*tangible objects on interactive surfaces,constructive assemblies of modular connecting blocks and token constraint system.*

Interactive Surfaces

Frequently, tangible objects are placed and manipulated on planar surfaces. Either the spatial arrangement of objects and/or their relations (e.g., the order of placement) can be interpreted by the system. Ex. Urp [39]

Constructive Assemblies

Modular and connectable pieces are combined in the same way that physical construction kits are. The system could interpret both the spatial organization and the order of actions. Aish, BlockJam, and Topobo, for example, have clever 3D modeling tool kits [40].

Token+Constraint systems

A hybrid of physical and digital objects Constraints provide structure (stacks, slots, racks) that mechanically constrain the positioning and movement of tokens while also providing haptic guidance to the user.The interaction syntax can be expressed and enforced via constraints. Marble answering machine and slot machine, for example [38].

2.3. Application of TUIs

According to the research some prominent application areas for TUIs are learning, planning and problem solving support, programming and simulation tools, information visualization and exploration support, entertainment, play, performance and music, and social communication.We have recently seen an even broader expansion of application examples, such as facilitating discussions about health information among women in rural India [41], tracking and managing office work [42], and invoice verification and posting [43].

2.3.1 TUIs for Learning

Many TUIs are computer-supported learning tools or environments. This is due to a number of underlying factors. To begin, learning researchers and toy designers have always augmented toys to increase their user experience and attractiveness.Second, physical learning environments engage all senses, promoting the child's overall development.

Digital Manipulatives

Digital manipulatives are TUIs that are based on educational toys such as construction kits, building blocks, and montessori materials. They are computationally enhanced versions of physical objects that enable children to investigate concepts involving sequential processes and computation [5].Concepts that are normally considered to be beyond the learner's abilities and age-related level of abstract thinking can be made accessible on a practical level using computationally enhanced construction kits.

- Lego MindstormsTM robotic construction kit have evolved from the MIT Media Lab Lifelong Kindergarten group.Lego Mindstorms is a hardware and software structure that creates programmable robots based on Lego building blocks. To build the mechanical systems, each version includes computer Lego bricks, a set of modular sensors and motors, and Technic Lego parts[1].
- Crickets are tiny programmable devices that can spin, light up, and play music. Crickets allows kids to make musical sculptures, interactive jewelry, dancing creatures, and other artistic creations while also learning important math, science, and engineering concepts.[2].Researchers from Lifelong Kindergarten previously worked with LEGO on the development of the LEGO MindStorms robotics kits, which are now used by millions of people worldwide. Crickets develop from the same tradition, but with a greater emphasis on artistic expression.The Playful Invention Company now sells crickets as a product[3].
- ChainForm is a linear, modular, actuated hardware system as a novel type of shape changing interface. Using rich sensing and actuation capability, this

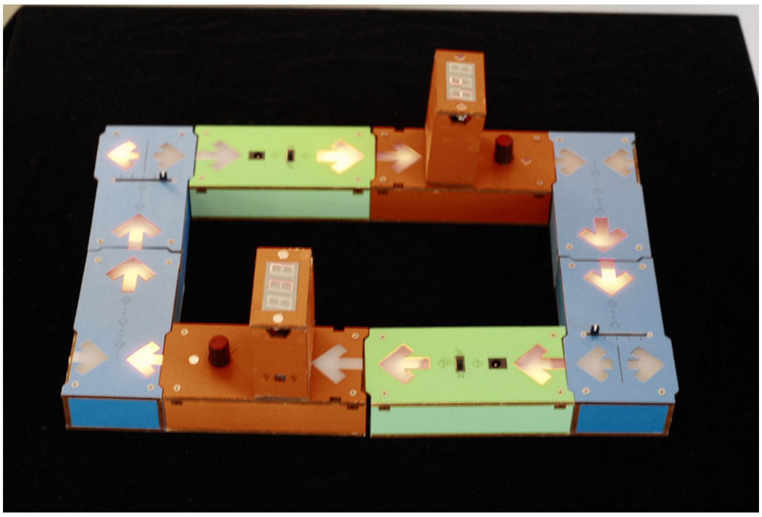
1 `https://www.lego.com/en-gb/themes/mindstorms`

2 `https://www.media.mit.edu/projects/crickets/overview/`

3 `www.picocricket.com`

modular hardware system allows users to construct and customize a wide range of interactive applications. Modules are equipped with rich input and output capability: touch detection on multiple surfaces, angular detection, visual output, and motor actuation. Each module includes a servo motor wrapped with a flexible circuit board with an embedded micro-controller [44] (See Figure: 2.7).

- FlowBlocks was created to allow kids to manipulate abstract structures of dynamic processes. It is a system that could "grow with the child," beginning with kindergartners learning to count and quantify and progressing to high school or college students struggling with calculus and statistics (Figure 2.6).FlowBlocks is intended to simulate counting, probability, looping, and branching concepts.



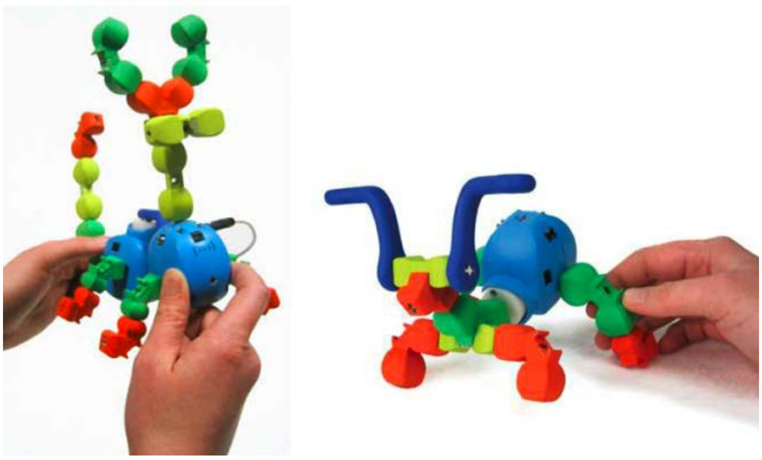
(Source article of Oren Zuckermanr,Saeed Arida and Mitchel Resnick 2005 [45])

Figure 2.6 FlowBlocks:*FlowBlocks,can simulate mathematical concepts such as counting and probability, as well as computer-science concepts such as looping, branching, and variables.*

- Smart Blocks is an augmented mathematical manipulative that allows users to investigate the volume and surface area of three-dimensional(3D) objects. The underlying principle of Smart Blocks is that when cubes are connected together, they form a shape that the system recognizes. More specifically, the system can calculate the volume and surface area of that shape and provide feedback to the user on these parameters.

Figure 2.7 From left to right:*ChainForm and Smart Blocks.*

- Topobo which is a 3D constructive assembly that combines creating model and playing with mechanics in order to teach the concepts of for kinetic knowledge. Topobo enables the building of robotic creatures from parts, where movement of special joints can be programmed individually through demonstration.



(Source Conference paper of Human Factors in computing system SIGCHI [40])

Figure 2.8 Topobo:*Constructive Assembly System with Kinetic Memory.*

2.3.2 Planning and Problem Solving Support

The broader category for TUI's are ;

1. Episematic Actions: Non-pragmatic manipulations of artifacts aimed at better understanding the context of a task,such actions have been shown to improve mental performance. TUIs can perform a wide range of epistemic actions, from rotating physical objects in space to arranging them on a surface.

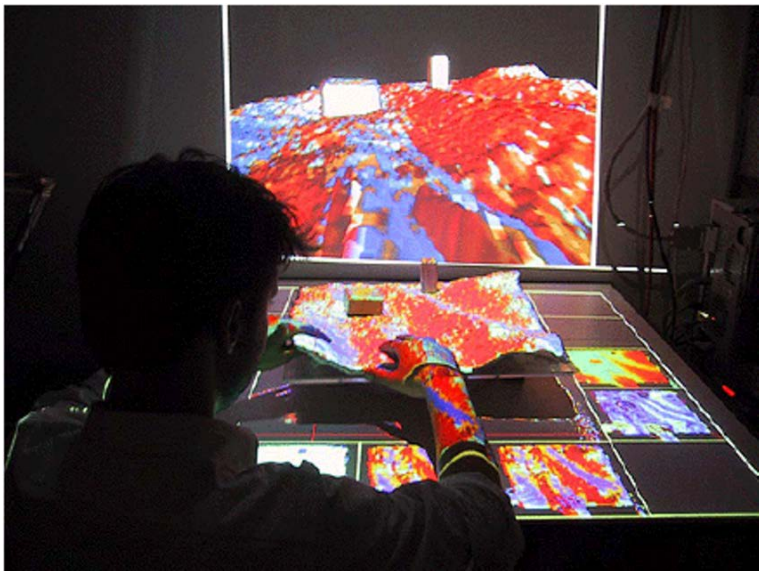
2. Physical Constraints: Physical constraints can use affordance to communicate interaction syntax and limit the solution space.

3. Tangible Representations of a Problem: Where the physical arrangement and manipulation of objects has a direct mapping to the represented problem, such as urban planning and architecture.

Some examples of this category are;

- SandScape is a physical interface for designing and understanding landscapes using a variety of sand-based computational simulations. Users can see these simulations as they are projected onto the surface of a sand model of the terrain. Users can select from a number of simulations that highlight the height, slope, contours, shadows, drainage, or aspect of the landscape model. The project demonstrates an alternative type of computer interface (tangible user interface) that capitalizes on our natural ability to understand and manipulate physical forms while also utilizing the power of computational simulation to aid in our understanding of a model representation [46].

- Pico is tabletop interface includes small objects (referred to as pucks) that can be moved by the user as well as sensed and moved by the interface surface.The Pico interface allows humans and computers to work together to solve complex optimization problems. While the computer optimizes a given problem based on predefined software constraints, the user can implement additional mechanical constraints in real time to explore alternative solutions [47].



(Source article of Piper, Ratti and Ishii [46])

Figure 2.9 SandScape:*A 3D Tangible Interface for Landscape Analysis.*

2.3.3 Information Visualization

Tangible user interfaces have the potential to improve interaction with visualizations by providing rich multi-modal representation and allowing for two-handed input. GeoTUI is a TUI for geophysicists that provides physical props for defining cutting planes on a projected geographical map on a surface. Geophysicists can select a cutting plane on the projected map by manipulating a ruler prop or selection handles. Geophysicists evaluated the system at their workplace. For a cutting line selection task on a geographical subsoil map, users of the tangible user interface outperformed users of a standard GUI, according to the evaluation [48].

2.3.4 Tangible Programming

Research has shown that tangible programming have been designed based on free play and exploration so it holds entertainment value but evidence has shown through studies that it has great benefits on kid programming language especially girls so such systems does offer concrete educational benefits [34].

- AlgoBlocks assists children in learning programming through the use of a video-game activity. The large blocks represent constructs from the Logo educational programming language. These can be linked together to form an executable program while at the time the command is executed, an LED on each block illuminates [49].

- Tern, is a tangible programming language for middle school and late elementary school students. It is made up of blocks that look like jigsaw puzzle pieces, with each piece representing either a command (e.g., repeat) or a variable. Tern's pieces' physical form determines what type of blocks (command or variables) and how many blocks can be connected to each piece [50].

(Source CHI Conference proceedings of Horn, Michael S. and Jacob, Robert J. K. [50])

Figure 2.10 Tern:*It consists of a collection of wooden blocks shaped like jigsaw puzzle pieces.*

2.3.5 Entertainment, Play, and Edutainment

Toys, entertainment, and edutainment related to TUI, TUIs have multiple application areas that overlap. The Nintendo Wii is perhaps the best illustration of a tangible entertainment device, and its commercial success shows the market potential of TUI-related systems. However, other examples that more closely match the TUI definition should not be overlooked. Many latest learning toys use tangible input, concrete representation, and digital augmentation. Neurosmith[4], for example, sells MusicBlocks, which allow children to create musical scores by inserting colored blocks into the toy body and varying and combining the basic elements. TUIs can be interpreted as many museum interactives that combine hands-on interaction with digital displays.Visitors to the Vienna Haus der Musik (Museum of Sound)[5], for example, roll two dice to select melodic lines for violin and recorder, from which a short waltz is automatically generated.

(Source from neurosmithtoys.com)

Figure 2.11 Neurosmith *Music Blocks.*

4 Neurosmith toys:because it's a small world.
`http://www.neurosmithtoys.com`

5 `https://www.hausdermusik.com/en/museum/`

2.3.6 Music and Performance

Music TUIs are either intended for the novice, providing a simple and easy-to-use toy, or for the professional, who values physical expressive power, comprehensibility, and visibility when performing electronic music in front of an audience. The reacTable[6] was created for implementations, casual users, and professionals who performs in concerts. It attempts to integrate immediate and intuitive access in a relaxed and immersive setting with the versatility and power of digital sound design algorithms, resulting in limitless progression and mastery. Several musicians can share control of the reacTable(See Figure 2.12) by touching, rotating, and shifting physical artifacts on the illuminated surface, constructing various audio topologies in a kind of tangible modular synthesizer or graspable flow-controlled programming language [51]. Audiopad is a musical performance interaction that

(Source ACM Conference on Expressive Character of Interaction [51])

Figure 2.12 reacTable:*Multiple hands at reacTable to make music.*

aims to integrate the modularity of knob-based controllers with the expressiveness of multidimensional tracking interfaces. A real-time synthesis process is controlled by the performer's manipulation of physical pucks on a tabletop(See Figure 2.13).

6 https://reactable.com

The pucks contain LC tags, which the system tracks in two dimensions using a series of specially shaped antennae [52]. Block Jam is a tangible user interface that uses 26 physical artifacts to control a dynamic poly rhythmic sequencer.These physical artifacts (See Figure 2.13), named blocks, are a novel type of input device for interacting with an interactive music system.The tactile nature of the blocks, combined with the user-friendly interface, encourages face-to-face collaboration and social interaction within a single system. The concept of collaboration is expanded further by connecting two Block Jam systems to form a network [53].

(Source from New Interfaces for Musical Expression NIME [52] [53])

Figure 2.13 From Left to Right:*Audiopad and Block Jam.*

2.3.7 Other Applications of TUI

Social communications and tangible reminders and tags are also some of the other domains where TUI applications can be seen. In connection to the social communication many research has been done. A variety of prototypes are being developed to address remote intimacy. In this context, researchers frequently experiment with various sensory modalities. Strong and Gaver [54], for example, present "feather, scent, and shaker." When you squeeze a small device while thinking of the other, feathers fall down a tube, activating a scent, and shaking it causes the other device to vibrate.Tangibles are well-suited to tagging and mapping applications, in which the tangible object is used to trigger digital information or functions.Holmquist et al [55] investigate the use of physical tokens to bookmark and recall webpages.

2.4. Tangible Thinking

Our physical bodies and the tangible things with which we interact shape our knowledge of the world. Through locomotive experience, child develops their spatial cognitive skills [56].Through bodily interaction with tangible manipulatives, kids learn abstract concepts. Physical artifacts are frequently used by practitioners such as designers, architects, and engineers to reason about complex problems. One of the advantages of TUIs over traditional user interfaces is that they facilitate tangible thinking — thinking through bodily actions, physical manipulation, and tangible representations [34].

2.5. Conclusion

Even though TUI is still a new and growing field of study, its theory and practice are insufficiently established for real-world applications. However, integrating the physical and digital worlds seamlessly is undoubtedly a goal for digital natives or immigrants today, as the digital world appears to undermine individuals of interactions with the physical world. TUIs gain the basic supporting points from emerging cognitive development (i.e., embodied cognition) that mind is just partial for and determined by body, which has a richer sphere than mind to interact with the environment. How to use TUI in education especially in mathematics as research shows that it is the neglected subject in early education [15]. The aim of this thesis is to address through a TUI design for kids mathematical learning focusing on geometry.

Chapter 3

TIEboard:Develop Kids Geometric Thinking through TUI

3.1. Concept Design

3.1.1 Importance of Geometry in Early Education

Geometry can serve as a core-relating science and mathematics. Geometry should be emphasized at all ages, grades, and years.'What does this have to do with the real world?'is a common criticism leveled against mathematics curricula. Geometry is the most important mathematical subject [21].It is central to physics, chemistry, biology, geology and geography, as well as art and architecture.It is also at the heart of mathematics, though the importance of geometry was obscured by fashionable abstraction for much of the twentieth century.

Teachers and curriculum writers all too often assume that children in early childhood classrooms know little or nothing about geometric figures. Furthermore, teachers have had little exposure to geometry in their own education or professional development. As a result, it is not surprising that most classrooms provide only basic geometry instruction. One early study discovered that kindergarten children already knew a lot about shapes and matching shapes before instruction began [16]. Their teacher tended to elicit and verify prior knowledge while not adding content or developing new knowledge.

3.1.2 TUI's and Traditional Manipulatives

Students are best served by learning concepts through actual manipulation of physical materials in order to give meaning to math teaching. Motivation is best achieved through active involvement with physical objects. The use of manipula-

tives particularly in geometry can create a level of excitement and enjoyment for the kids. Aim of manipulatives is to teach students a geometric principle in more than one way. In other words, rather than just hearing about a mathematical principle, they get to see and feel it.
There has been a growing interest in developing digital manipulatives, also known as TUIs, to promote learning over the last two decades [57]. In contrast to traditional manipulatives, which uses no technological interaction like geoboard, tangram puzzles, tangible interfaces allow users to interact with digital information through physical objects. Tangible interfaces are less machine-centered and more user and task-centered, opening up new ways for different types of people to interact with digital content. In the education field, tangible interfaces provide a new opportunity for abstract concepts to be grasped and possibly understood by children.

3.2. Research Goals and Direction

3.2.1 Research Goals

The main goals of this thesis are;

- The aim of this research is to take advantage of children's deep familiarity (and profound affection) for traditional manipulatives by using them as a starting point. Simultaneously by seamlessly integrating computational abilities in the traditional learning toys to develop tangible interactive ways for kids to learn abstract concepts.
- To create a working prototype of new digital manipulative(TUI's) that takes inspiration from traditional manipulatives, and show that TUI's have a greater potential to engage children, therefore potentially promote learning especially with the abstract concepts.

3.2.2 Research Direction

As highlighted in the preceding chapters this research is about creating a tangible manipulative for early geometry learning by taking the inspiration from traditional manipulatives as to take advantage of kids profound affection with them. The significance of using physical objects for child development has been extensively researched and has shown that kids actively build knowledge through their interactions with words, people, and things. In contrast TUIs enable children to engage, simulate, and create knowledge through direct manipulation and also allow for richer experiences [57]. Interacting with appropriate materials initiates a creative thinking spiral in which *children imagine what they want to do, design a project based on their ideas, play with their creations, share their ideas and creations with others, and reflect on their experiences* [58]. This research aims to develop a digital manipulative inspired from traditional geoboards that are widely used in the early education. The goal is to take advantage of TUI's so kids can have memorable experiences and learn better as the literature review has shown that TUI's promote learning in contrast to traditional manipulatives. Additionally the new TUI manipulative will be based on research based curriculum **"Building Blocks for Little Kids"** [1] so teachers can use it in their classrooms.

Target Audience

We aim to target children in a range of 5 to 9 years old as research shows that geometric learning is neglected in early education. Students' lack of competence in geometry is a problem not only for geometric topics, but for other mathematical topics as well as other subject-matter domains [42].

3.3. Ideation

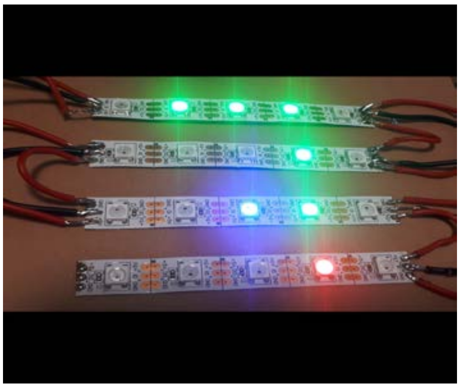
This research started with traditional geoboards as a starting point to create initial prototype by seamlessly computing technology within the physical manipulative for kids to have memorable learning experiences.

3.3.1 First Prototype

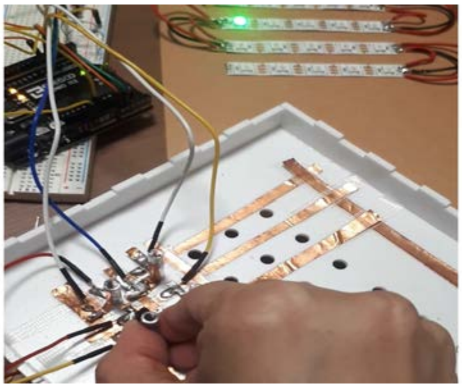
The first experimental prototype(See figure 3.2) was developed based on the traditional geoboard(See figure 3.1). In this prototype neopixels were controlled with

ArduionIDE to provide different feedback to make shapes. Red light in the figure shows(See figure 3.2) that a mistake has been made and correct placement was shown with the blinking neopixel. In order to make the design more interactive sensing connection was developed using copper tape. Further developments in prototype were done after first successful prototype with neopixel tape.

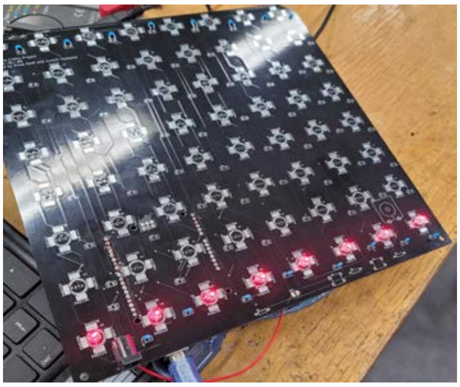
(a) Traditional Geoboard



(b) First Prototype



(c) Sensing Connection



(d) Eagle Customized PCB Board

Figure 3.1 Initial Ideation

3.3.2 Tangeo Board

Tangeo Board abbreviates as *Tan-tangible and Geo-geoboard*. First experimental prototype was further matured to do initial testings with kids and iterations to be done if required. Eagle software was used to create a customized Tangeo board file(See Figure 3.1).

3.3.3 Tangeo Board:Design of Instruction

Tangeo board main idea is to give feedback to the children while they are making shapes that whether they are doing wrong or right. As a first basic idea, the user passes a string or rubber band through the pins according to the visual instructions on the board. Then the location of the first pin to hang the string is visually indicated by a flickering LED. The aim was to give guidance through a red light, and when kids do correctly, it changes its color to green as positive feedback. With such kind of interactive feedback kids tend to engage more with Tangeo board and could have memorable learning experiences.

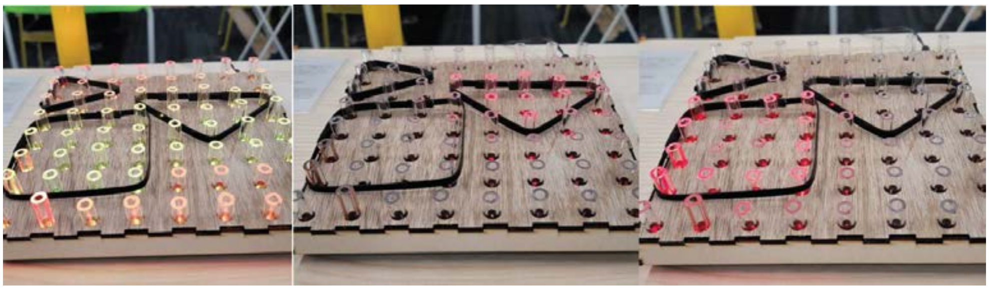


Figure 3.2 Tangeo Board.*Digital Manipulative(TUI) inspired from traditional geoboard.*

3.3.4 Sensing Connection of Tangeo Board

When moving on to the following process,we wanted to increase the interaction for more engagement. Therefore, we developed a method to sense the pin connection by using conductive rubber automatically. The resistance of the conductive rubber is 1.2x100.(Ohm.cm),and its diameter is 5mm(See Figure3.3).By controlling the matrix with eight horizontal pins over eight vertical pins, it is possible to sense which pins are connected to each other.For the microcomputer, we used an Arduino Uno.

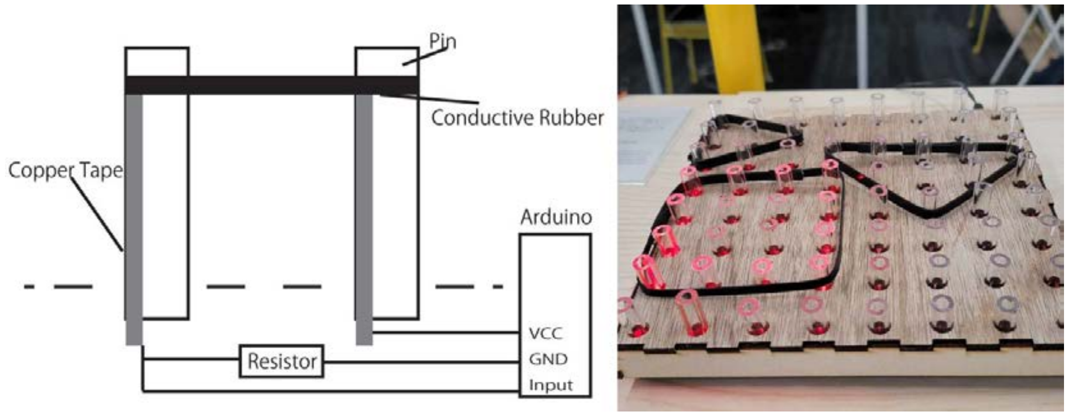


Figure 3.3 Sensing Connection of Tangeo Board

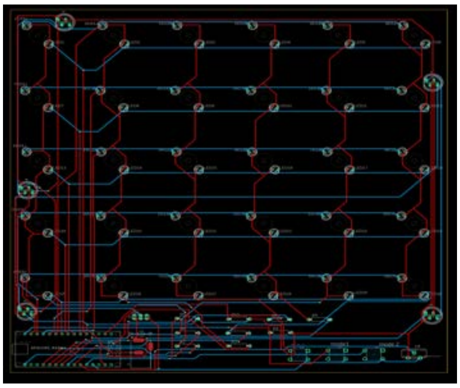
3.3.5 Limitations of Tangeo Board

When enthusiastic young kids used our Tangeo Board, multiple problems consistently occurred,pointing us to the limitations of our device. Tangeo Board could not engage kids for longer time as it lacks physical interaction and interesting feedback. Additionally, conductive rubber was not that flexible for the kids to use, also the one color(black) conductive rubber seems boring. The size of Tangeo Board is big for the kids to hold and make shapes. We plan to address these problems in future prototypes.

3.4. Second Prototype

3.4.1 System of TIEboard

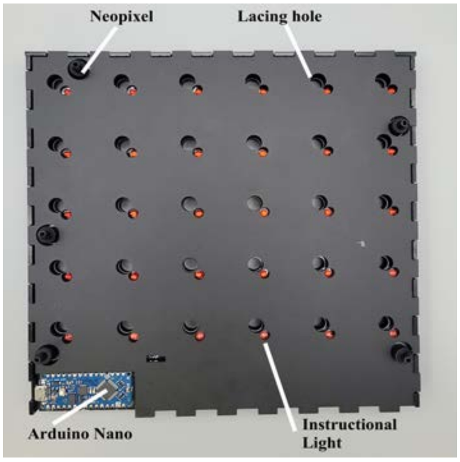
As the boundary between the physical and digital world blurs, TIEboard focuses on physical interactions for kids to have memorable learning experiences.TIE in TIEboard can be abbreviated as ***"Tangible Interface for Education"***.We redesigned the TIEboard PCB board with ergonomic dimensions and improved interactions (See Figure 3.4). Arduino Nano was added for enhanced programming and buttons to change the modes.The size of the holes are 7mm to lace the string in this case optical fiber, and the number of holes is five vertically and six horizontally.TIEboard essentially have two sides **Top** and **Bottom**. LEDs are



(a) Eagle PCB layout

(b) Customized TIEboard PCB

(c) TIEboard *Top side*



(b)TIEboard *Bottom Side*

Figure 3.4 TIEboard Technical Drawing

placed next to each of the holes on both sides of the board. Buttons are placed on top side of TIEboard so it will be easier for kids to access them and change the modes/steps. Neopixels and arduino nano are placed on the bottom side of TIEboard(See Figure 3.4).

3.4.2 TIEboard: Design of Instruction

This research idea is inspired from traditional geoboards that are being used to explore geometry in early education. We aim to target the age group of 5-9 years old kids as the product will incorporate different levels from easy to complex to cater the needs of shape learning during the early education. As a first basic idea, the user passes a string of optical fiber(1.5mm to 3mm) through the holes according to the visual instructions on the board(See Figure 3.7.The user selects the shape according to the level/age by pressing the mode switch.Then the location of the first hole to lace the string is visually indicated by a flickering LED. Then, after lacing the thread on the first hole,the LED for the next instruction will light up by pressing the button.The product will teach kids on different levels according to their skills that are based on **Building blocks for little kids** [1], a research based curriculum and will also improve their attention. Users can learn simple shapes, concepts such as similarity and symmetry, and even complex geometric shapes.In addition users can also make original shapes using ArduinoIDE.

3.4.3 Changing String Color

The color of the thread could not be changed dynamically in the normal geoboards and Tangeo board prototype. However in order to make the design more interactive and fun to play with we have introduced a method where kids can pass through the string(in this case optical fiber) to make shapes and along the way their string will glow with their choice of color and kids can even mix colors by controlling the neopixel LED's.In this case, we used an optical fiber (acrylic material) with a diameter of 1.5mm to 3mm for illumination. The optical fiber of 1.5mm allows kids to make more complex shapes as it enables them to lace multiple times from a single hole.The size of the holes are 7mm, and the number of holes is five vertically and six horizontally.LEDs were placed next to each of the holes on both sides of the board. While kids are lacing through to make shapes their shape learning is reinforced with colored optical fiber feedback. In this proposed design single color LED's are provided along the holes for appropriate guidance through variation in the blinking. After they finish passing through the hole, a button is pressed to get the next direction for the fiber to pass through.

3.4.4 Modes of TIEboard

Colors of Neopixels

There are total of 5 neopixels, out of which 3 neopixels are given primary colors that are *red, yellow and blue* while other two are given secondry colors that are

Figure 3.5 Lace optical fiber to make shape

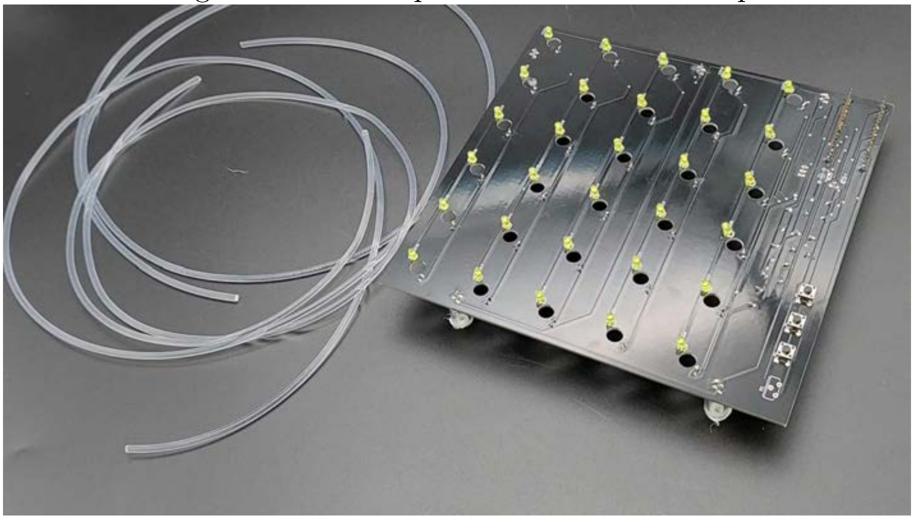


Figure 3.6 Step by Step Guidance

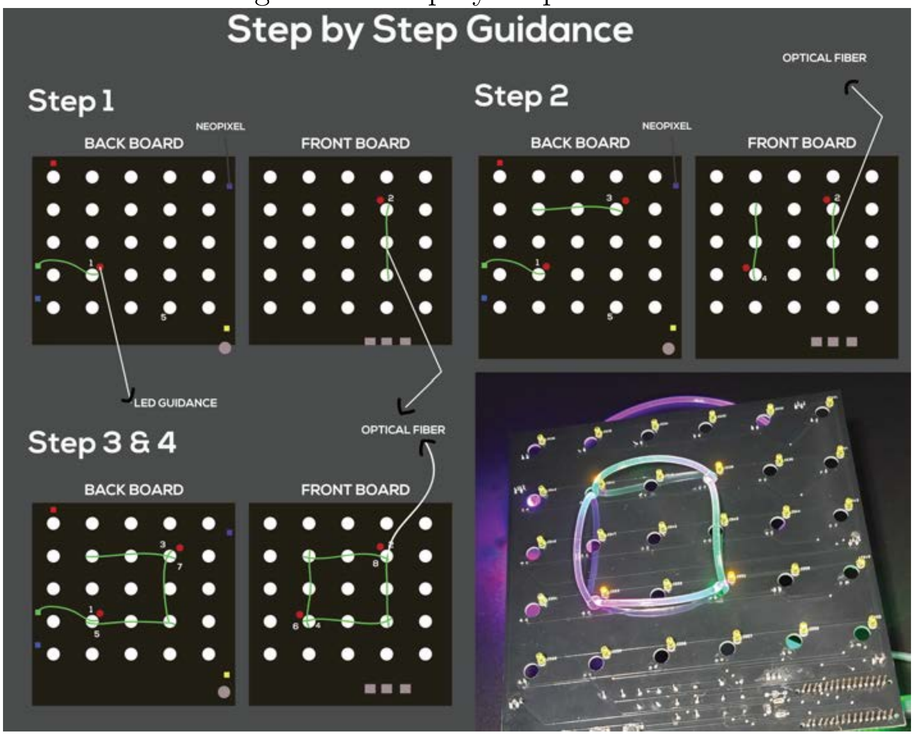


Figure 3.7 TIEboard:Design of Instructions

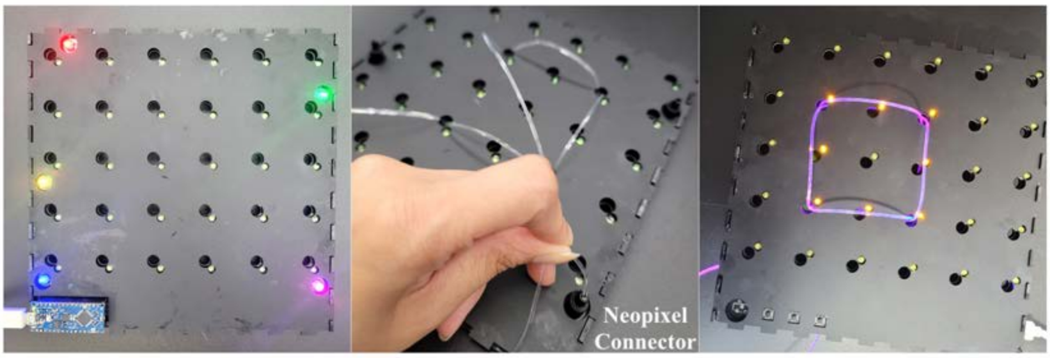


Figure 3.8 TIEboard: *Shape learning is reinforced with colored optical fiber feedback and mixing colors by controlling neopixel*

purple and green (See Figure 3.8). Aim to give colors in this way so kids can have multiple mixed color options. As TIEboard targets the age group of 5-9 years old kids, it incorporates different levels from easy to complex to cater the needs of shape learning during the early education across this age group. The product will teach kids on different levels according to their skills that are based on **Building blocks for little kids** [1] [15], a research based curriculum and will also improve their creativity. Users can learn simple shapes, concepts such as similarity and symmetry,complex geometric shapes and collaborative learning.TIEboard modes are as follows;

Table 3.1 Modes of TIEboard

Mode Number	Mode Description
Mode 1	Basic Shape
Mode 2	Different Orientation and Size
Mode 3	Symmetry
Mode 4	Complex Shape
Mode 5	Collaboration
Mode 6	Free Play

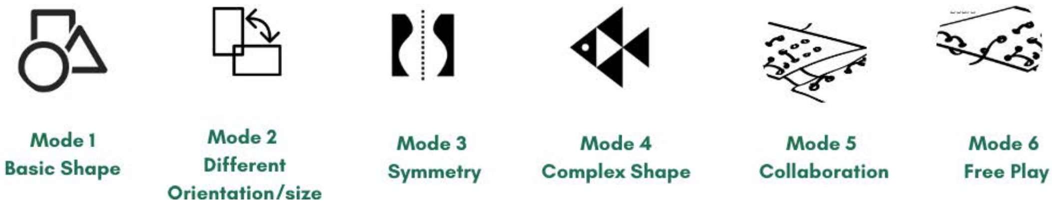


Figure 3.9 TIEboard: *Modes inspired from Building Blocks for Little Kids [1]*

(a)Mode 1 (b)Mode 2 (c)Mode 4

Figure 3.10 TIEboard Modes

Mode 1: Basic Shape

TIEboard basic shape mode focuses on teaching basic shape to Kids with one by one instructions through LED's(See Figure3.10).To begin, a complete shape appears for kids to identify, shape followed by one by one instructions on pressing the next button. It aims to teach shapes like triangles, squares, rectangles, quadrilaterals, pentagons and hexagons. With shapes like hexagon kids can also make shapes within shape to reinforce basic shape learning.

Mode 2: Different Orientation and Size

This mode aims to teach that even if the shape is of different size and in different orientation it is still the same shape. This mode advances by not giving one by one guidance to make shapes in contrast it gives complete shape guidance. For each step three different shapes will appear that kids will lace and in the end they can sort the odd one out shape by giving a unique color to it. For this mode neopixels have been defined with red and green color so it will be easier for the kids to give a different color to the odd shape(See Figure 3.10).

Mode 3: Symmetry

Symmetry mode focuses on shapes(butterfly or fish) that teaches children different lines of symmetry that include;

1. Horizontal Symmetry
2. Vertical Symmetry
3. Diagonal Symmetry

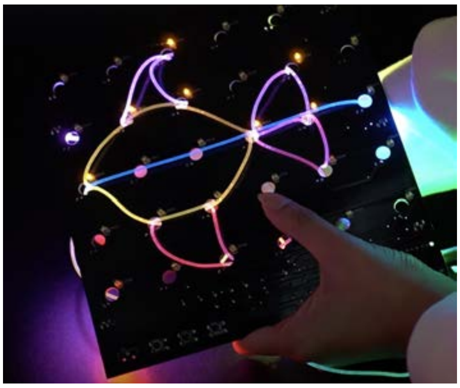
Instructions are given only for one half of the shape and other half of the shape is laced by memorizing the steps that were done before or by observing the shapes kids have already created. Unique colors can be given to line of symmetry and to different shapes(See Figure 3.11).

Mode 4: Complex Shape

This mode aims to give different parts guidance of one shape and once they finish lacing all the parts by following LED's instruction they can see a familiar shape that they witness in their daily life, example includes; umbrella,sunglasses and apple. Kids can then color their shape as they like(See Figure 3.10).

Mode 5: Collaboration

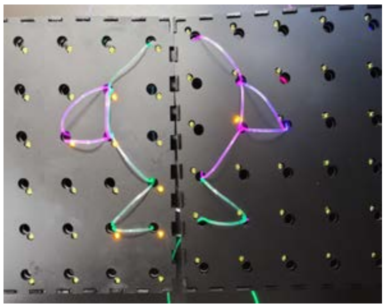
Collaboration mode focuses on social learning as research shows that social interaction and imitating one another,children acquire new skills and learn to collaborate with others. We intended to provide guided collaboration through LED's and free collaboration that could encourage social interaction and increase engagement and usability. Secondly,this mode also deals with collaborating TIEboard in different directions for instance vertical and horizontal that allow children to explore and engage more(See Figure 3.12). Once a complete shape is created through social interaction kids can color their shape collaboratively.

(a)Instructions given for one half (b)Horizontal Symmetry


(c)Vertical Symmetry (d)Diagonal Symmetry

Figure 3.11 Mode 3: *Symmetry*

(a)Horizontal Collaboration (b)Vertical Collaboration

Figure 3.12 Mode 5: *Collaboration*

3.5. TIEboard:Creative Learning

3.5.1 Creative Learning

Creativity is an essential aspect of children's education [59]. Creativity should not be overlooked in school education because it is a necessary skill for the twenty-first century."Creativity is regarded as an essential skill that leads to the creation of knowledge and the construction of personal meaning [60]." Tangible user interfaces (TUIs) open up new avenues for creative learning [59]. Research shows that TUIs had many advantages,including the following:(1) they are novice-friendly,(2) support children's cognitive process and development,(3) enhanced their initiatives, (4) allows them to think outside the box, and (5) encouraged communication and collaboration in a meaningful context.

3.5.2 Mode 6:Creative Learning with Free Play

TIEboard can provide new potentials to facilitate creative learning through a natural, interactive interface with its *free play* mode. Free play mode is designed to allow kids explore different designs of their own choice. This mode offers three different versions of neopixel lights for kids to play around;

1. One color neopixels(in this case all red)
2. Different color neopixels
3. Blinking neopixels

This mode does not provide any instructions, by the time kids reach to this mode they are mature enough to explore TIEboard with free play. TIEboard free play mode opens up different domains of creative designs like **"Neon Art** and **"Stop Motion Animation**.

Glowing Acrylic Modules

In order to increase the playfulness of free mode we have designed modules of different shapes that kids can use to make their creative shapes.

Figure 3.13 Mode 6 Free Play:*Glowing acrylic modules for free play.*

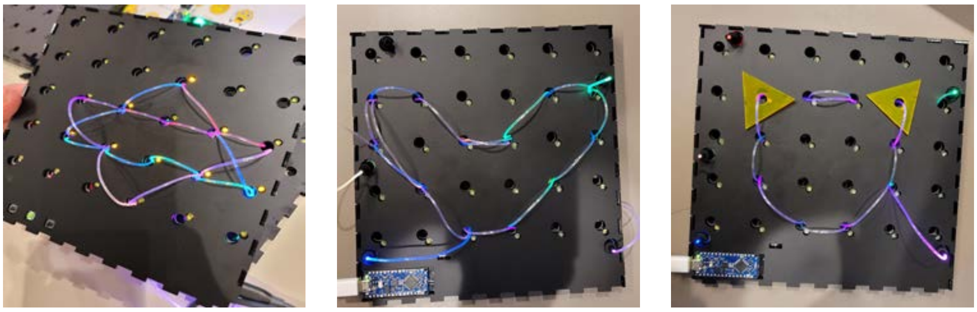
Neon Art

Neon art is a relatively new medium in which neon lights are used to create visually stimulating works of art, which frequently include motion and interactivity[1].TIEboard will allow kids in one color and different color neopixels to make creative art that may resemble neon art and they can use it to decorate their room or study table. **TIEboard holes configuration** can also be changed to create more flexible neon art. Holes configuration can be change by adding more holes in the acrylic frame of TIEboard that will allow kids to add 3D printed pins to it to get more lacing points and option to even pass through the optical fiber in order to create interesting neon art.

Stop Motion Animation

Stop motion animation (also called stop frame animation) is animation that is captured one frame at time, with physical objects that are moved between frames.When you play back the sequence of images rapidly, it creates the illusion

1 `https://spiegato.com/en/what-is-neon-art`



(a)Star (b)Bear (c)Cat

Figure 3.14 Creative Deisgns with Free Play

of movement[2]. Blinking neopixels versions can allow kids to make basic stop motion animation to get an idea how it works.Different timings can be set on Arduino IDE for each neopixels in order to create the moving illusion of the shapes kids will create on TIEboard.

3.5.3 Advantages of Creative Learning with TIEboard

Early childhood is a critical stage in the development of creativity. Children are naturally inquisitive and unrestrained [60]. TUIs have an indirect impact on children's creativity in five ways:(1)they scaffold beginners with varying skill and knowledge levels to lower their knowledge thresholds for creative activities; (2)encourage intrinsic motivation by facilitating exploration and self-directed creation;(3) they encourage children's cognitive process by reducing cognitive efforts for imagination and spatial thinking, allowing children to have multi-dimensional perceptions and more flexibility in their creative activities [59].

3.5.4 Conclusion

Holding an optical fiber in their hands and lacing around the TIEboard to learn geometry and create shapes, provides children with a multiple sensory experience. Children's bodies and senses are spatially located within the experience itself, and

2 `https://www.dragonframe.com/introduction-stop-motion-animation/`

this immersion in the task is essential for learning [27].
Traditional graphical user interfaces (GUIs) have very limited communication channels, failing to embrace the richness of human senses and skills acquired over a lifetime of interaction with the physical world [30]. This ability to engage children is due to the fact that TUIs correspond to children's animistic conception of the word at this age. This ability to project life into objects and interact with them is a critical component in learning and development, bringing empathy to the service of intelligence and providing, like a good toy, mental space for playful exploration: raising children's interest, curiosity, and willingness to try out and explore new materials, allowing them to experience the world in a new way.

Chapter 4
User Study and Evaluation

4.1. User Study and Evaluation

This section reports a study that evaluated the abilities of both TIEboard and traditional geoboard in terms of user experience and collaboration.Research shows that *children's user experience* in terms of ease of use and fun influences their attitude to using the learning application and the effectiveness of the learning process [61] [62].In this respect three research questions were defined that are;

Table 4.1 Research Questions-User Experience(RQ-UX)

Research Questions	RQ-UX(A) How are both version TIEboard and traditional geoboard perceived by the participants? RQ-UX(B) What are the general impressions of participants towards the activity in both boards? RQ-UX(C) What are the general impressions of participants towards collaboration and free play mode?

Table 4.2 Hypothesis (H-UX(A)

Hypothesis-H-UX(A)	H-UX(A1) Kids find TIEboard more fun to use because it is more interactive. H-UX(A2) The participants find TIEboard easy to use. H-UX(A3) There are no differences between both version of activity in terms of perceived ease of use.

Table 4.3 Collaboration Research Question and Hypothesis

Research Question (RQ-C)	How is the quality of the collaboration achieved by using TIEboard?
Hypothesis (HC)	H-C1 TIEboard enables good collaboration quality in terms of Meier et al collaboration dimension. H-C2 Collaboration let kids understand complex shapes better together.

To answer the research question RQ-UX(A) three hypothesis were developed (See Table 4.2)With respect to the evaluation of collaboration, the research question was defined. To answer this question,nine collaboration dimensions defined by Meier et al [2] were taken into consideration. These will be detailed later when the evaluation instruments are described(See Figure 4.2). According to these dimensions the following hypothesis were defined (See Table 4.3). Additionally, the following research question and hypothesis is considered with respect to the performance (See Table 4.4).

Table 4.4 Performance Research Question and Hypothesis

Research Question	RQ-P Is there any difference between both versions(TIEboard and traditional geoboard) in the time spent making a shape?
Hypothesis	H-P TIEboard takes less time to make shapes compared to traditional geoboard.

4.1.1 Participants

Total of sixteen children(10 boys and 6 girls) of age 5-10 years participated in this study. Study was conducted in three different workshops to focus on different aspects of TIEboard.

Table 4.5 Workshops (Compare TIEboard v/s Geoboard)

Workshop Location	Number of Kids	Aim
Community Furatto Asagaya	8	Initial Testing for design iteration
Panasonic Centre	4	Test Mode 1 to Mode 4
Community Furatto Asagaya	4	Test Mode 1-Mode 6

4.1.2 Procedure

The study was conducted in the presence of the observers. Each child had 1 hour 30 minutes approximately in each workshop we conducted.

- Initial workshop lasted for 1 hour 30 minutes the aim of this workshop was to observe the kids response towards TIEboard and iterate if needed.
- Second workshop at Panasonic lasted for 1 hour the aim was to give kids traditional geoboard first and then TIEboard to compare the Mode learning from 1 to 4.
- In the second workshop it was noted that traditional geoboards should have been given to kids after TIEboard for better comparisons. Third workshop was for 1 hour 30 minutes and aim of this was to first give TIEboard so kids can play all the modes and then the traditional geoboard.

In general we did not specify any time limits or perfect outcomes from the task, but the children were asked to complete one shape for each mode. Video was recorded for qualitative analysis. Two observers had to score kids on collaboration over nine dimensions based on Meier et al [2]. All children were keen to take part and seemed to enjoy the experience. At the end of the study, we distributed a set of usability questions that the children had to answer.

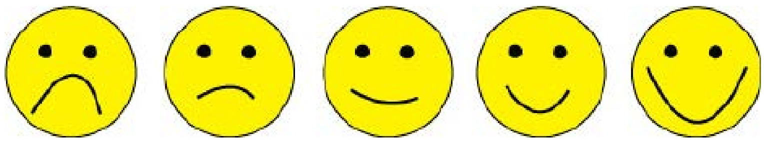
4.1.3 Evaluation Instruments

For all the three workshops cameras were set to record the TIEboard activity for qualitative analysis. We designed usability questionnaires to answer our research questions that we developed. We posed questions regarding three main aspects in usability to compare TIEboard with traditional geoboard which are effectiveness, efficiency and satisfaction. Some of the questions were structured into the organization of information, highlighting the ease to make shapes, learn complex shapes, instructions with TIEboard, easy to understand abstract shapes. To measure the fun aspects, we asked questions concerning free play mode and creativity, pleasant surprises and enjoyment with colored optical fibre.

1. **Second Workshop** : Pre-questionnaire was filled after using traditional geoboard while Post-questionnaire was filled after using TIEbaord at the end of workshop(See Appendice A.1).

2. **Third Workshop** : Comparison questionnaire (TIEboard v/s traditional geoboard) was given at the end of workshop(See Appendice B.1).

For both workshops – usability and fun questionnaire – we adapted the smileyometer methods, replacing the traditional discrete likert type scale. The smileyometer has been used for different research before and is said to be one of the most appropriate indicators to be used when the testers are children [63].



(Smileyometer (adapted from Read et. al., 2006) [63])

Figure 4.1 Smileyometer:*indicates emotions of children. From left to right: awful, not very good, good, really good, and brilliant.*

Collaboration Meier rating scheme nine dimensions

Additionally the quality of the collaboration (RQ-C) was assessed, as pointed out above, with the questionnaire designed by Meier et al. [2]. This questionnaire consists of nine dimensions associated with five different aspects of collaboration, which were filled by two independent observers after the activity in a 4-point likert Scale ranging from minus 2 (very bad) to positive 2 (very good), with only the endpoints of the scale being named.

Communication
Dimension 1: Sustaining mutual understanding
Dimension 2: Dialog management

Information Processing
Dimension 3: Information pooling
Dimension 4: Reaching consensus

Coordination
Dimension 5: Task division
Dimension 6: Time management
Dimension 7: Technical coordination

Relationship Management
Dimension 8: Reciprocal interaction

Motivation
Dimension 9: Individual task orientation

(Collaboration Nine Dimensions (adapted from Meier et al 2007) [2])

Figure 4.2 Collaboration Nine Dimensions:*Meier rating scheme dimensions.*

(a)Workshop 1 (b)Workshop 2 (c)Workshop 3

Figure 4.3 Workshops

The Guilford Measures: measuring kids creativity

Psychologist J. P. Guilford devised four measures of a person's divergent production. Each of the measures can be practiced and improved, and each focuses on creative output in the context of a prompt (any prompt) that asks for a quantity of responses([1]).

1. Fluency: how many responses
2. Flexibility: how many types of responses
3. Originality: the unusualness of the responses
4. Elaboration: the detail of the responses

4.2. Results

4.2.1 Performance

The time spent in each workshop with TIEboard was less than the time taken to make shapes on geoboard. The time taken to complete shapes on both the board was noted down during the workshop and were later verified with the videos taken during the workshops.Therefore, in order to answer the research question RQ-P in light of the time observed,we could accept H-P(See Table 4.4).

Figure 4.4 Performance:*Time observed during workshops for TIEboard v/s Geobaord.*

1 `http://www.senseandsensation.com/2012/03/assessing-creativity.html`

4.2.2 User Experience

Workshop 1 (See Figure 4.3) lead us iterate the design in terms of material and we changed the wooden frame to black acrylic matte finish for better glowing effect of optical fiber. As figure(4.9 and 4.10) shows,the participants having high expectancy as well as high levels of perceived fun towards the TIEboard compared to traditional geoboard in both the workshops(workshop 2 and 3) that were conducted. The results from both the workshops show that hypothesis H-UX(A1) developed under the research question of RQ-UX(A) which states that kids find TIEboard more fun to use because of being more tangible and more interactive can be accepted.Also both the workshops clearly reported that Kids enjoyed learning geometry with TIEboard compared to traditional geoboard. Children perceived ease of use towards both TIEboard and traditional geoboard was also analyzed as a part of RQ-UX(A), this being close to fantastic and good for TIEboard which led us to accept H-UX(A2) and reject H-UX(A3) as traditional geoboard ease of use was close to being ok.With respect to RQ-UX(B) participants impressions towards the activity in the TIEboard was high compared to geoboard(See Figure 4.7 and 4.8).Complex shape learning like symmetrical shapes were more fun and easy to learn with TIEbaord with 90 percent kids responded towards it while only 35 percent participants responded in favor of symmetry learning with traditional geoboard. Participants enjoyed changing color optical fiber as compared to the simple thread of traditional geoboard. Glowing optical fiber also attracted kids to explore and make more shapes with TIEboard(See Figure 4.8. TIEboard also act as a huge motivation factor to learn more complicated shapes.

"I now want more challenging shapes and challenging modes with TIEboard."

"I want to extend optical fiber to make more complex shapes."

"Symmetrical mode was fun as I could learn complex shapes and it was easier to understand symmetrical lines with TIEboard glowing thread."

Figure 4.5 Workshop 1: Comparison of TIEboard v/s Geoboard

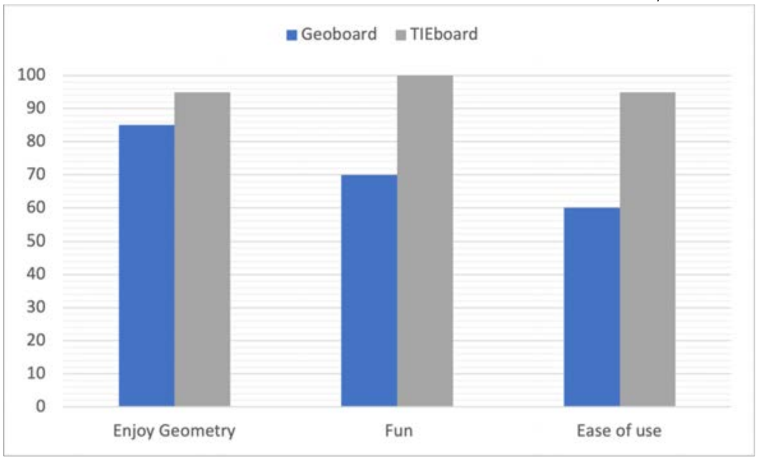


Figure 4.6 Workshop 1:Kids responses toward TIEboard

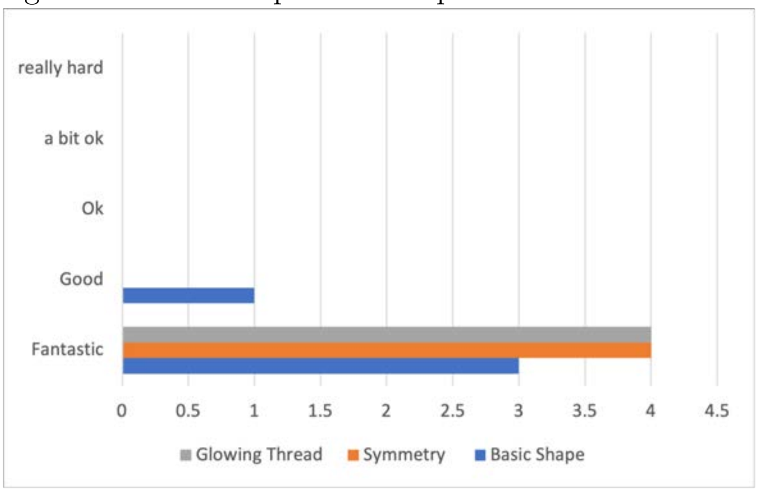


Figure 4.7 Workshop 1:Results of TIEboard v/s Geoboard

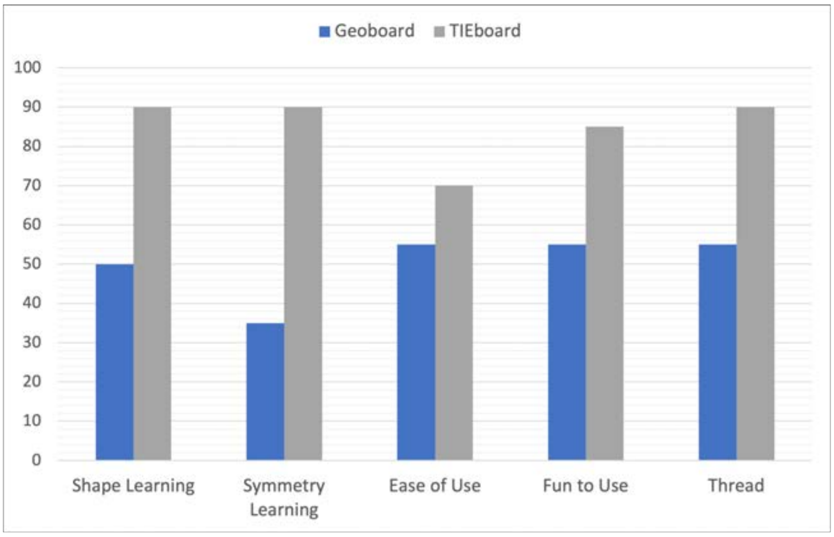


Figure 4.8 Workshop 2:*Activity recorded through smileyometer questionnaire during workshop for TIEboard v/s Geobaord.*

Figure 4.9 Workshop 1:*Pre-Questionnaire Smileyometer responses for Geoboard.*

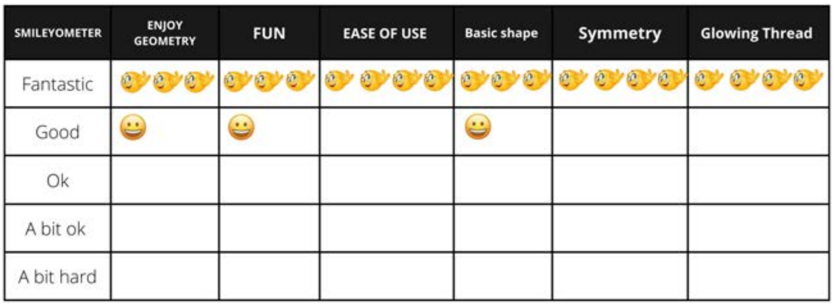


Figure 4.10 Workshop1:*Post-Questionnaire Smileyometer responses for TIEboard.*

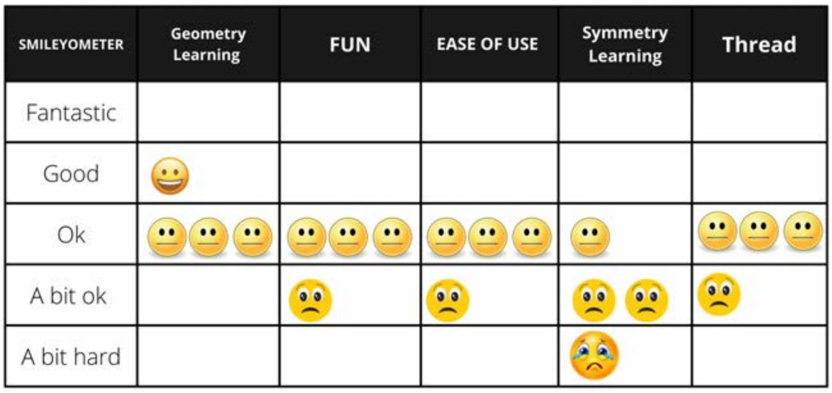


Figure 4.11 Workshop 2:*Comparison Smileyometer Questionnaire for Geoboard.*

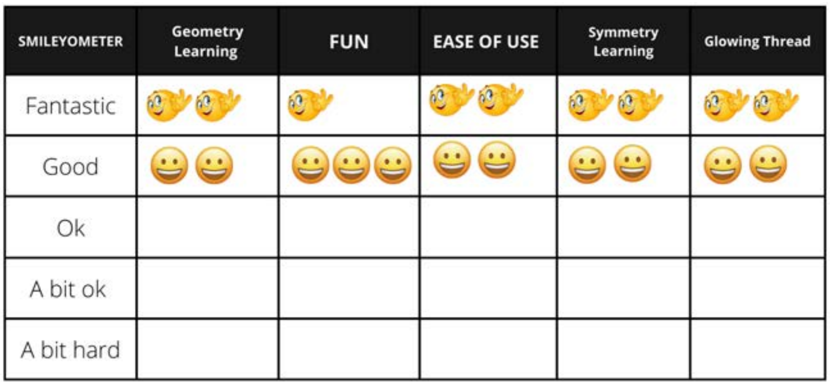


Figure 4.12 Workshop 2:*Comparison Smileyometer Questionnaire for TIEboard.*

4.2.3 Qualitative Analysis with Video Recording

Third workshop was recorded with two different angles to observe activity of Kids with TIEboard and overall observations were made by asking questions with participants. To do qualitative analysis a reference book has been used "Video in Qualitative Research" [64]. The book has described three main analysis steps with video recording.

1. Preliminary review -*cataloguing the data corpus* (See Appendice B.2)
2. Substantive review of the data corpus (See Appendice B.3)
3. Analytical review of the data corpus(Mapping out the details) (See Figure 4.13)

Preliminary review involves cataloguing some basic aspects of the activities and events that have been recorded during the workshop(See Appendices).**Substantive review** of the data was more focused and arise in the light of initial analysis of data extracts or "fragments". It was performed to find further instances of events to study kids learning behaviour with TIEboard,kids common behaviour when they are making shapes with TIEboard and also to enable the comparison of TIEboard with traditional geoboard (See Appendices).**Analytical review of the data corpus** involves transcribing event in fragments and mapping out the details or coding similar attributes that kids had while doing the activity with each TIEboard and traditional geoboard(See Figure 4.13).

4.2.4 Collaboration Mode Analysis

Figure(4.16)depicts the scores for each collaboration dimension specifically for the collaboration mode of TIEboard as the mean values calculated by two observers for two groups having two participants.This Figure(4.15) shows the individual responses of two observers for each collaboration dimension for TIEboard collaboration mode.The analysis of the figures lead us to accept H-C1 and H-C2 (See Table:4.3) since there was on average good collaboration quality in terms of corresponding dimensions.The group 2 did not show good understanding on *"Reaching Consents"*, however observers agreed that overall both the groups enjoyed and worked better with interesting shapes in collaboration mode.

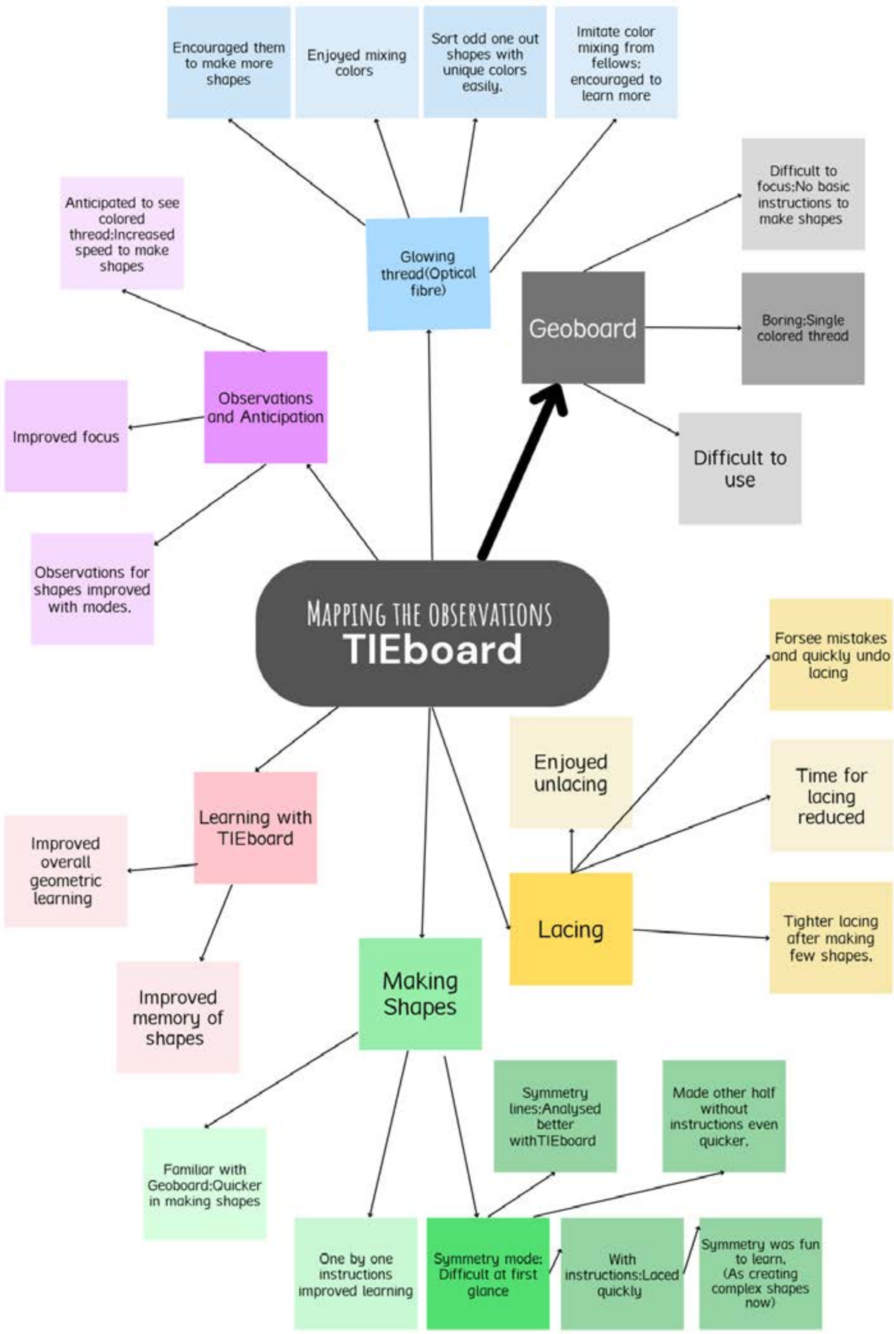


Figure 4.13 Analytical Review: *Transcribing/Coding events in segments.*

(a)Group 1 (b)Group 2

Figure 4.14 Collaboration Work

Group 1:"We realized in the middle that we had to make sure in which direction our TIEboards should collaborate and it was a fun fact as in different orientation we could create different kinds of shapes."

Group 2:"We thought to make some shapes on each TIEboard and later collaborate but we realized in the end that it would have been better to decide clearly in the beginning on the shape so we did not have to rush in the end to complete our shape."

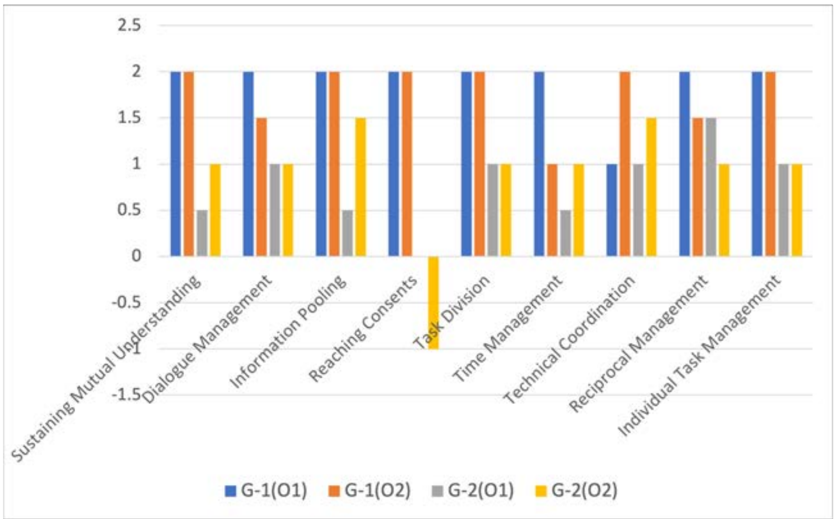


Figure 4.15 Collaboration Dimensions [2]:*Analysis of individual observers.*

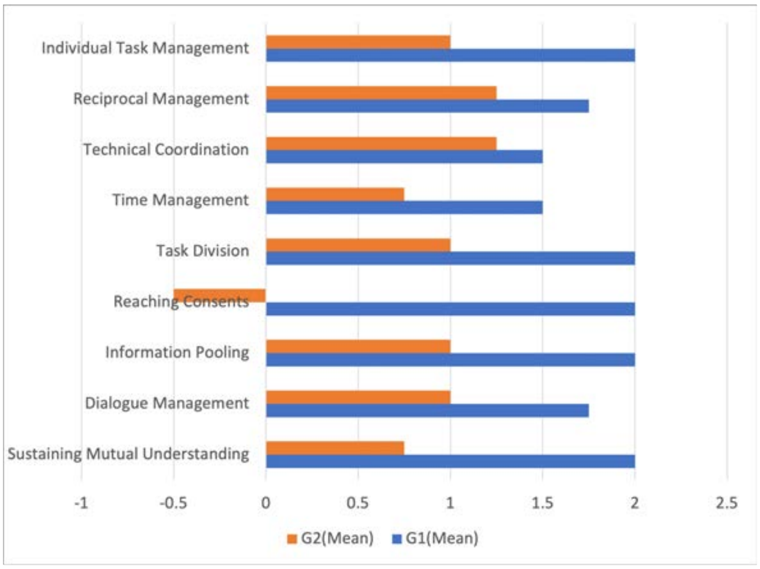


Figure 4.16 Collaboration Dimensions [2]:*Mean Analysis of two observers.*

4.3. Analysis of Geometric Learning

Based on the analysis done throughout the modes it was analysed that kids understanding as well as interest for geometric learning increased. Geometry is a

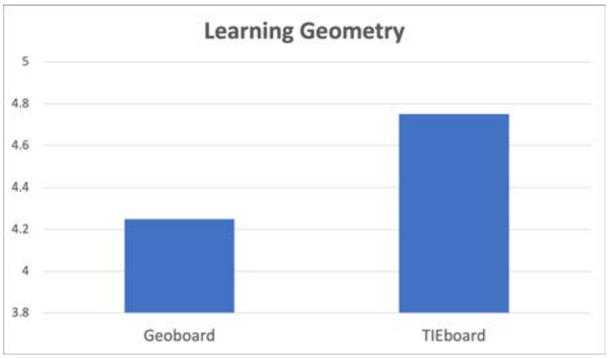


Figure 4.17 Geometric Learning: *TIEboard v/s Geoboard*

branch of mathematics concerned with the study of lines, line segments, rays, angles, and geometric shapes. The contents are designed to teach students how to measure line lengths, angles, perimeters, and areas of 2D shapes [65]. We observed the increased in understanding of shapes,sides and angles along the modes of TIEboard that was evident through kids impressions in workshops.

*8 years old ' Mode 2:"Oh look I found the odd one out shape because it has a different angle than the other two."**[workshop3]***

*7 years old ' Mode 2:"I recognized the odd one out shape due to different length of sides of each shape."**[workshop3]***

*5 years old ' Mode 3:"I can see a triangle in my butterfly."**[workshop2]***

*9 years old ' Mode 3:"My fish has hexagon and triangle and it was easier with glowing fiber to understand the line of symmetry of fish and I quickly made the other half."**[workshop3]***

*Group1 ' Mode 5:"Ops! we should have connected the TIEboards in this direction to make this shape."**[workshop3]***

4.3.1 Challenges with Traditional Curriculum

Challenges of traditional curriculum have been improved with TIEbaord(See table 4.6).

4.4. Creative Learning with TIEboard

Creative learning is an essential part of kids education. TIEboard provides new possibilities for creative learning through its free play mode. Results shows(See Figure 4.19) that TIEboard has many advantages, for kids creative learning such as (1)novice-friendly,(2)supported children's cognitive process and development,(3) promoted them to make unique designs with blinking pattern,(4) encouraged them to think outside the box, and (5)encouraged collaboration and communication in an authentic context.

Traditional Learning	Learning with TIEboard
Educational factors are boring,inappropriate teaching,more focus on numeracy than geometry,not realizing the potential of kids for mathematical learning. Traditional tools like geoboard,tangram puzzles having no interaction with kids.(Time consuming)	TIEboard modes are developed on research based curriculum Building Blocks for Little Kids.Take less time to learn different modes because of being interactive.Will be easier for the teachers to teach geometry in sequence with TIEboard.

Table 4.6 Challenges of traditional curriculum improved with TIEbaord learning

4.4.1 Free Play Analysis

In order to measure creativity,the *Guilford Measures* that measures person's creativity have been used in this study. We asked four kids(6-10 years old) in our third workshop to take approximately 30 to 40 minutes to make five free designs in free play mode that offers further three versions (1) Fixed Light (2) Different Light (3) Blinking Light,they were asked to make three designs in each version and then make two or more designs in their favorite version. We receive the following responses to evaluate creative aspect with fluency,flexibility,originality and elaboration(See Figure 4.19). The responses might be evaluated in the following way;

- Kid 1 made two responses but were comparatively more detailed and had a thought process like the first design is Santa and Christmas ornament and second is the crown. So this kid has highest *Elaboration.*
- Kid 2 made most of the responses,even though designs were some how similar to a cat. So this kid has highest *Fluency.*
- Kid 3 made fewer responses than Kid 2 but responses are unique from each other. So this kid has highest *Originality.*
- Kid 4 made types of responses,even though has has fewer total responses than Kid 1.So this kid has the highest *Flexibility.*

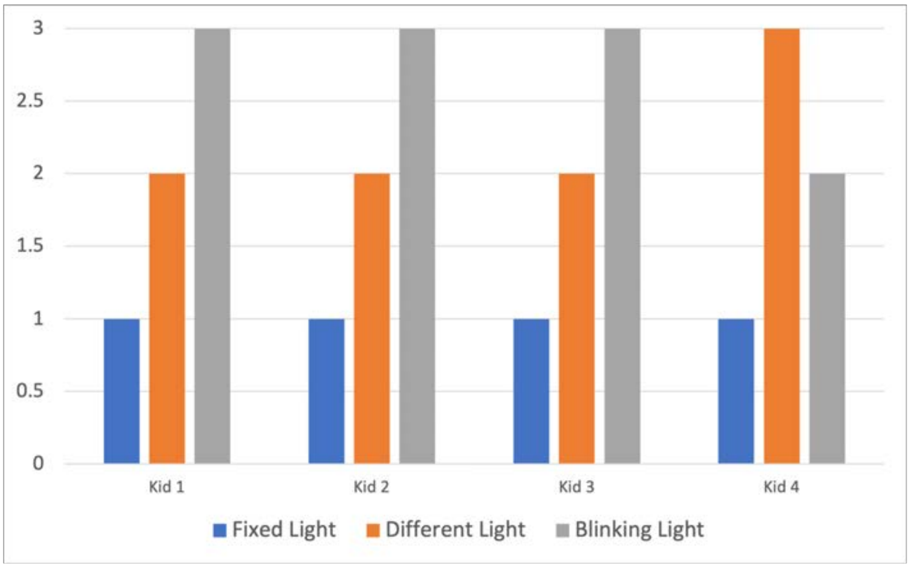


Figure 4.18 Free Play Mode *Kids favorite version out of (1)Fixed light, (2)Different light, (3)Blinking light.*

During the workshop we also asked kids to rank three different versions of free play mode(See Figure4.18). Most of the kids enjoyed blinking light version,as blinking lights was motivating them to make certain designs. Blinking light version is a unique feature of TIEboard as it is not offered in analogous products so all the kids enjoyed working with the blinking version(See Figure 4.18).

Kid 1:"I got inspired to make Santa and Christmas ornaments from blinking pattern."

Kid 2:"My favorite version is blinking and it motivated me to make my favorite pet cat to make it look cute."

Kid 3:"Blinking pattern is so much fun,I feel, I can make moving things so I made a wheel with blinking light."

4.5. Conclusion

A study conducted with sixteen children (5-10 years old) has revealed that a better user experience is provided with TIEboard which in turn leads to improved

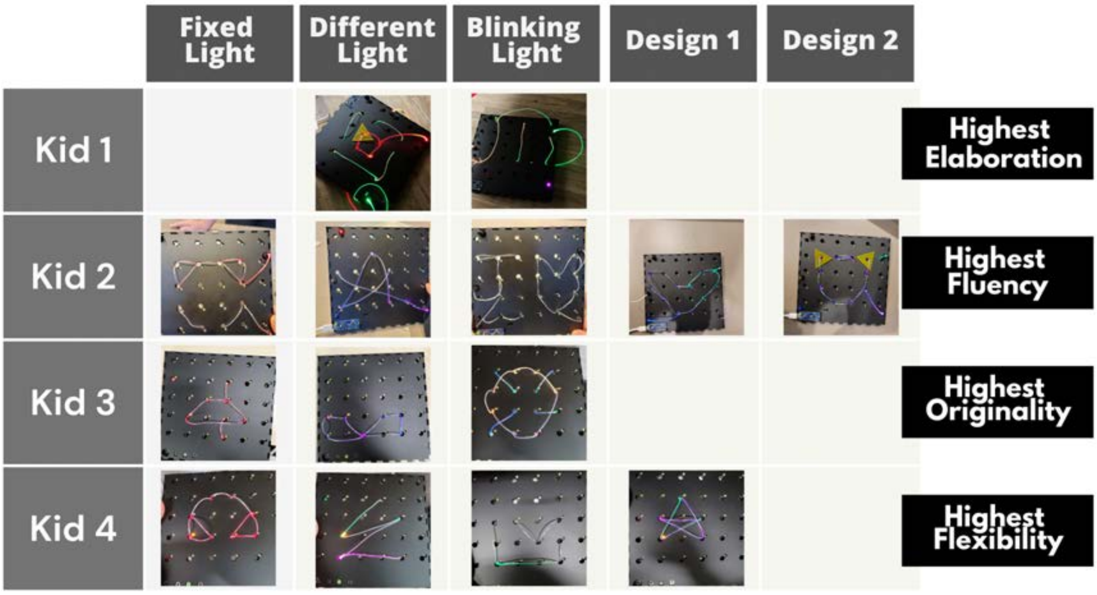


Figure 4.19 Guilford Measure:*Free Play Analysis.*

geometric learning compared to traditional geoboards. Observations with respect to performance showed that TIEboard took less time to complete shape compared to geoboard while making a similar shape. An analysis of the quality of the collaboration around nine dimensions has revealed good collaboration in both groups of third workshop. Additionally kids geometric learning got improved with the modes as they started communicating in mathematics language. The results obtained for free play mode revealed TIEboard to be perceived by children as generally engaging and encouraging to make creative designs, with blinking light being the most favorite for most of the participants. Additionally, it would be interesting to study the geometric learning, with TIEboard and geoboard over a long period of time with the same groups and later compare the two groups learning after specific time. Finally, further research could be conducted to assess how TIEboard can meet the different needs posed by different learning settings and students; in particular, to support inclusive learning.

Chapter 5
Future Work

5.1. Future Work

5.1.1 Sensing Connection in TIEboard

When moving on to the following steps in specific mode, manually pressing a button *to go to the next step* might cause a mistake in the procedure. Therefore in future we would like to develop sensing connection in the TIEboard. Some of the possibilities that we have looked into are as follows;

1. Dycotec DM-SNW-8010S[1] is a transparent conductive screen silver nanowire printable paste used in thin film PV, display, sensors, and general printed electronics. The paste is safe to use on glass and plastic substrates like PET and poly carbonate. After putting the paste on required surface in this case optical fiber it needs to be cured at 140 degree Celsius for 20 minutes, which makes it transparent and conductive.

2. Photo-interrupter is a transmission-type photo sensor that works by detecting light blockage when a target object comes between both elements, acting as an optical switch. Photo-interrupters, as opposed to mechanical switches, are non-contact (optical) switches that improve reliability by preventing abrasion wear (contact). These photo-interrupters can be placed around each hole of TIEboard matrix so it can detect every time optical fiber is being laced through the hole.

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1 `www.dycotecmaterials.com/wp-content/uploads/2019/02/Dycotec_TDS_DM-SNW-8010_Datasheet.pdf`

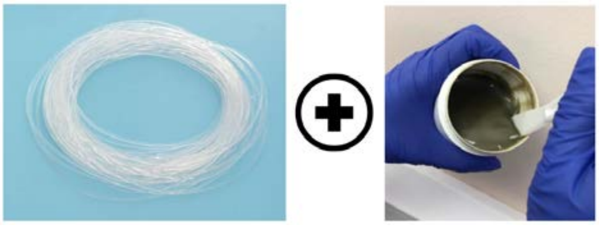


Figure 5.1 Dycotec DM-SNW-8010S: *Transparent conductive coating on optical fiber.*

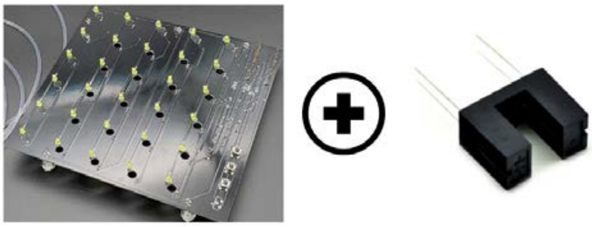


Figure 5.2 Photo-interrupter: *To be placed around each hole of TIEboard.*

5.2. Possible Features of TIEboard

5.2.1 Holes Configuration

Holes configuration can be customized in future TIEboard to increase the possibility of its uses in different contexts such as;

Neon Signs

Neon Sign will have better resolution if users can customize the holes configuration. This can also be done with in the existing TIEbaord frame by placing 3d printed small cylinders in the new holes created in TIEboard frame. By doing so users can lace as well as pass through to increase the resolution of final design(See Figure 5.3).

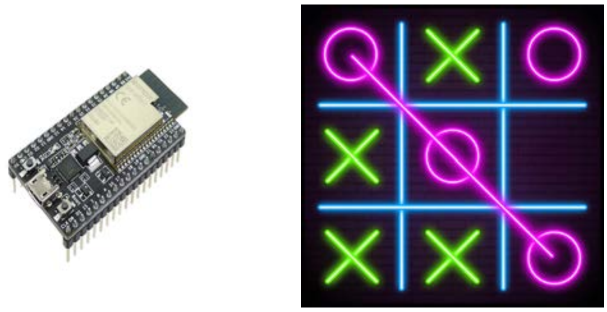
Isometric

With customized holes configuration kids can learn isometric views of different shapes.

Figure 5.3 Holes Configuration: *Better resolution neon signs.*

5.2.2 Collaborative Games

In order to introduce collaborative games, ESP32 should be incorporated instead of arduino nano. With ESP32 it would be easier to take advantage of the WIFI connection and play games in collaboration. One of the example of a simple game that can be introduced to evaluate the collaborative game mode with TIEbaord is **TIC TAC TOE**.



(a)ESP32 (b)TIC TAC TOE Game

Figure 5.4 Collaborative Games

5.3. Conclusion

During the workshops it was observed that TIEboard can have endless possibilities. It can also be used to visualize 3D-Shapes for better understanding of kids geometric learning. Additionally, different mathematical concepts can also be taught on this such as;perimeters or area of 2D surface. In one of the workshop at *Panasonic Center* we got the feedback that TIEbaord can be introduced at rehabilitation centers for elderly people. Based on this different TIEboard users can also be experimented to further modify the design.
With regard to the distribution of TIEboard is concerned we now focused on introducing it through workshops to our users and specific users can order us which can be consider as business to customer(b2c). However, in the future we would like it to expand as business to business and distribute it to schools so it can be included as a part of their curriculum as TIEboard modes have been designed on the research based curriculum **"Building Blocks for Little Kids"** [1].

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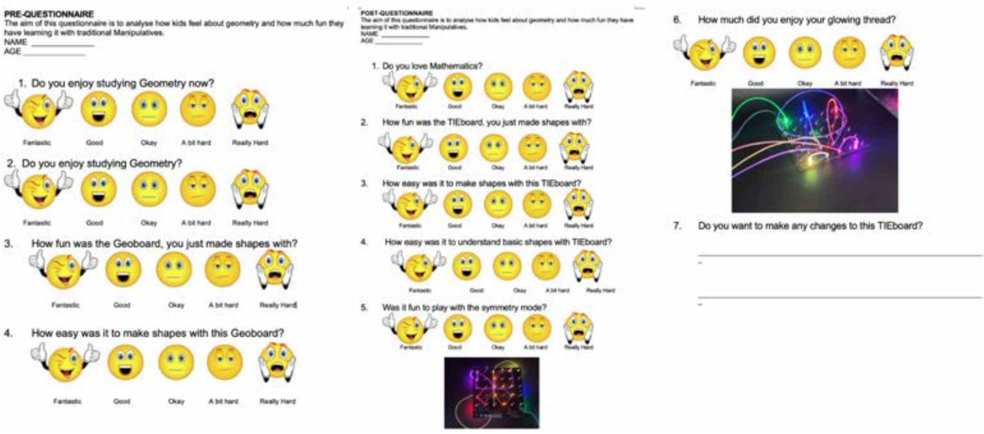
Appendices

A. Second Workshop Pre and Post Smileyometer Questionnaire



PRE-QUESTIONNAIRE
The aim of this questionnaire is to analyse how kids feel about geometry and how much fun they have learning it with traditional Manipulatives.
NAME ____________
AGE ____________

1. Do you enjoy studying Geometry now?
Fantastic Good Okay A bit hard Really Hard

2. Do you enjoy studying Geometry?
Fantastic Good Okay A bit hard Really Hard

3. How fun was the Geoboard, you just made shapes with?
Fantastic Good Okay A bit hard Really Hard

4. How easy was it to make shapes with this Geoboard?
Fantastic Good Okay A bit hard Really Hard

POST-QUESTIONNAIRE
The aim of this questionnaire is to analyse how kids feel about geometry and how much fun they have learning it with traditional Manipulatives.
NAME ____________
AGE ____________

1. Do you love Mathematics?
Fantastic Good Okay A bit hard Really Hard

2. How fun was the TIEboard, you just made shapes with?
Fantastic Good Okay A bit hard Really Hard

3. How easy was it to make shapes with this TIEboard?
Fantastic Good Okay A bit hard Really Hard

4. How easy was it to understand basic shapes with TIEboard?
Fantastic Good Okay A bit hard Really Hard

5. Was it fun to play with the symmetry mode?
Fantastic Good Okay A bit hard Really Hard

6. How much did you enjoy your glowing thread?
Fantastic Good Okay A bit hard Really Hard

7. Do you want to make any changes to this TIEboard?

Figure A.1 Pre and Post Questionnaires: *Second Workshop.*

B. Third Workshop Smileyometer Questionnaire

In third workshop instead of pre and post questionnaire we just did one comparison questionnaire after the workshop.

B.1 Video in Qualitative Research

Preliminary review cataloguing the data corpus and Substantive review of the data corpus are attached here.While Analytical review is in user study and evaluation(See Figure 4.13).

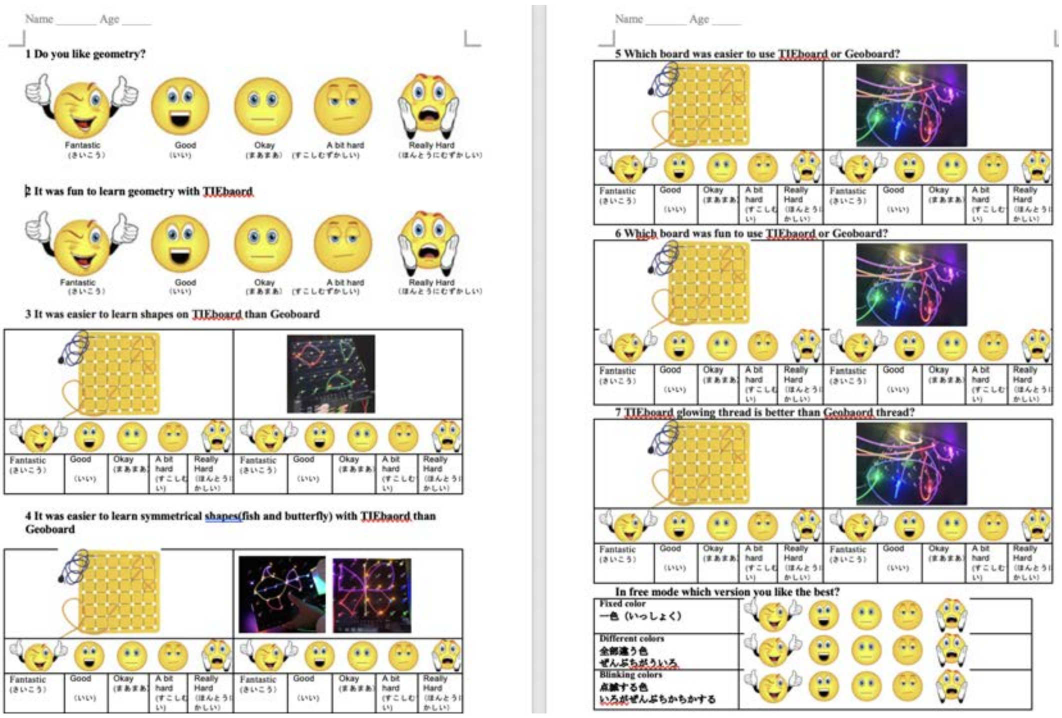


Figure B.1 Comparison Questionnaire: *Third Workshop.*

Users	Age	Findings	Time	Notes
G1	10	She was the quickest one to make shapes. She was good in the modes where there was not one by one instructions	58mins	She was focused and her analysis was good for shapes.
G2	8	She understood TIEboard quickly and enjoyed mixing colors a lot. Lacing got better after first mode.	65mins	Quick learner and started analysing her own mistakes and corrected quickly.
B1	9	He was impatient to complete shapes and made mistakes. But later he was quickly making shapes without error.	65mins	He sometimes used to look at other kids to get an idea. But he was good in lacing.
B2	7	He was really focused though slowest in all but was observing every step and was not making any errors.	68mins	He was enjoying the TIEboard a lot and was observing everything very keenly.

Figure B.2 Preliminary review: *cataloguing the data corpus*

Users	Findings with TIEboard	Mode and Time	Notes
G1	Made neat shapes,anticipated to see glowing threads and mixed colors after seeing other girl.She was quick to make shapes that didn't have one by one instructions.She quickly finished symmetrical shape first half and second half on her own.Other kids got inspired see her fish color.Her speed got better with every mode and was quick to make complex shapes with little or no difficulty.	Mode1 6mins, Mode2 7mins, Mode3 8mins, Mode4 7mins, Mode5 10mins, Mode6 20mins	She already worked with TIEboard in the very first workshop but she only played MODE 1 in that workshop. But this helped her to do better analysis with TIEboard.Kids were looking up to her as she was finishing first and was a source of inspiration for others. Last but not the least she was extremely focused in making shapes. She had an idea how traditional one works but it was hard to make shapes.

Figure B.3 Substantive Review of the data corpus

Users	Findings with TIEboard	Mode and Time	Notes
G2	She got used to TIEboard after the first mode and spent good enough time in mixing color.After the first shape she learned how to lace tighter to make neat shapes.Analysed quickly how to make shapes without one by one instructions.Analysed both top and bottom before making the shapes so was not wasting time in completing shapes in the bottom. She took little help to finish the symmetrical shape but was quick to finish it.She quickly foresee her mistakes and corrected it.	Mode1 8mins, Mode2 8mins, Mode3 10mins, Mode4 8mins, Mode5 10mins, Mode6 23mins	She was dropping thread in the beginning but later her lacing got better.Initially she was not foreseeing the problems she might face with rough lacing like loose shapes but later she started making tighter shapes.She found traditional one really difficult and stopped working with it.

Figure B.4 Substantive Review of the data corpus

Users	Findings with TIEboard	Mode and Time	Notes
B1	He was extremely impatient to complete shapes and see the results due to which he had to redo shapes in mode 1. He attained focused with coloring thread.He was good in making shapes without one by one instructions.Initially he thought that symmetry mode is difficult but later he quickly completed it and was really good in analysing symmetrical shapes and really enjoyed in mixing colors.	Mode1 8mins, Mode2 8mins, Mode3 10mins, Mode4 8mins, Mode5 10mins, Mode6 23mins	His focus gor improved. His lacing also got better with the modes,he sometimes used to look at other kids to see how they are doing to complete modes.His lacing was good with traditional geoboard but overall he didn't enjoy it as it wasn't guiding him or giving him the option of changing colors.

Figure B.5 Substantive Review of the data corpus

Users	Findings with TIEboard	Mode and Time	Notes
B2	It was difficult for him to grip the thread in the beginning but was extremely focused,he took time to finish first mode but his focus was good so he learned quickly how to do better lacing.He was excited to make fish and analysed the symmetrical shape so he don't have to redo anything. He started lacing and making shapes really nicely.He enjoyed coloring his fish and mixing colors.He was making really very neat shapes,and started enjoying even more.	Mode1 9mins, Mode2 8mins, Mode3 10mins, Mode4 8mins, Mode5 10mins, Mode6 25mins	Though he was slow compared to other kids but he was extremely focused in analysing each steps and hardly made any error.He quickly understood how to lace. He was enjoying the unlacing process.He did not really enjoyed the geoboard as he found it difficult to lace especially the complex shapes without instructions. Also as there wasn't any dynamic color changing in the thread he quickly got bored.

Figure B.6 Substantive Review of the data corpus