A Tangible E-Learning Solution for Early Childhood Development

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***Abstract*—Exploration and manipulation of physical objects are essential for early childhood learning. TangiGuru is an e-Learning platform that allows children to engage with real-world physical objects to provide that essential experience within an e-Learning application. TangiGuru consists of 12 tangible, manipulative objects known as TangiCubes, which are used as a tangible user interface between children and the e-Learning application. It can carry out cognitive learning activities related to colors, languages, shapes and basic math by dynamically varying assigned values by changing the external appearance of TangiCubes. This dynamic nature of the TangiCubes makes it possible to use the same tangibles with endless possibilities compared to traditional tangible learning solutions with static value for each tangible. With the initial observations of how children interact with computers, laptops, and mobile devices, the goal is to provide a playful interface for children by taking the approach to embedding and integrating technology into the children's daily activities. After the prototyping phase, children were evaluated with the traditional tangible learning solutions compared to TangiGuru. They concluded that the more interactive tangible interfaces could make the children perform activities more engagingly.**

***Keywords*—TangiGuru, TangiCube, Tangible User Interface, Tangible Learning, e-Learning, Embedded Systems, Human-Computer Interaction (HCI)**

I. Introduction

In recent years Human-Computer Interaction (HCI) has been focusing on Graphical User Interface(GUI), which allows the interaction through virtual objects through a computer screen, keyboard, or mouse. Now, a new research field has evolved as Tangible Interfaces, which grabbed the attention of HCI researchers to overcome the limitations GUIs contained. The terminology came from the early 90s, defined as a representation of digital information and controls to grasp using the hands. [1]

In the beginning, the research on tangibles started with prototyping oriented. Here, researchers tried integrating design and innovation into physical objects such as cubes, cards, and puzzles. First, some products were created that can be manipulated directly for different domains, such as music, storytelling and programming. [1]

Collaboration and playfulness are critical factors in the user experience of tangible learning solutions. [2] There is not enough research evidence that recorded user experience or other factors inside tangible learning for children. In this paper, we propose a novel tangible interface called TangiCubes. TangiCube is a tangible user interface with an OLED display, LEDs, and a vibration motor that can give the user direct outputs. There are sensors embedded in the tangibles to identify the motion of the tangibles and evaluate the activities. The design will rely on two main aspects.

- Children can learn better when playing and exploring the physical world. [3]
- Physical activities aid them to develop the cognitive skills [3]

The purpose of TangiGuru is to make learning more interactive for the children while improving their cognitive skills. TangiGuru consists of 12 interactive tangible components, known as TangiCubes here onwards. They will aid the children in performing the learning activities. TangiCubes will contain a humanoid interface to keep the children more interactive and engaged with the cube. Also, they are interconnected with a GUI to deliver the activities using a central hub to manage data communication.

This research will open up a new aspect because, in previous work, there were evaluations between the GUI and TUIs. However, we combine the TUIs and GUIs in this research to evaluate the outcomes. This study includes how TangiGuru aids the children in performing their cognitive learning activities compared to the traditional tangible learning solutions and GUI-based e-Learning solutions.

This paper is structured as follows. First, our solution is introduced in detail. In section II,III,IV,V,VI,VII, and VIII the background for conducting this research, research methodology, technology that is implemented, technology constraints, user experience and the research results, and conclusion discussed respectively.

II. Background

The researchers are trying to go beyond the traditional GUIs to give a better user experience to the users. [4] A new research field evolved to identify the relationship between digital information and physical information, where the Tangible user Interface word was defined by led Ishi and Ulmer back in 1970. [4] The TUI aims to make computers ubiquitous. Novel learning opportunities can be designed to integrate into kindergarten and school. Most activities are disconnected from the desktop or mobile device environment, as the younger ones are expected to play and move forward with the real world. Children aged 4 to 7 will interact with the real world, manipulate different objects, and explore. [3] The tangible user interfaces allow direct manipulations between the children and the object. According to constructive learning with these tangibles, [4] children will learn while exploring and solving problems.

Tangibles have been studied as a user interface in HCI research. Zhi Ying et al. investigate the use of a foldable 3D cube interface combined with augmented reality technology in the field of interactive storytelling. Camerata et al. employ tangibles as physical bricks to explore a virtual museum's data space, using people's intuitive grasp of 3D spatial connections. [5] In a recent project, designers created a TV remote control device by using the low cost of a tangible cubical object, rotating it, and laying it back down to scroll through a list of video streams representing six favorite shows. [3] Turning the cube would zip through the programs, and placing the cube back on a flat surface would output the top-lying video stream on the TV. The cube had no screens on its surfaces and was only used as an input medium. When building their learning appliance, they considered the tangible cube as an interface for various learning exercises for children of varying ages. The challenges were identifying thewoe same image, a word-picture association, a vocabulary trainer, and matching several different 2D perspectives. [5] These applications are based on the cube's exploratory affordance and the building of a semantic relationship between physical control and digital output. The suggested spatial geometry learning appliance takes a step ahead by establishing a semantic connection between physical control, digital output, and abstract notion, hence offering a redundant learning interface.

The Topaoko building kit includes a microprocessor, sensors, an actuator, and hardboard components. It enables users to create their embedded-circuit kit and experiment with kit components. With roBlocks (now Cubelets), peoplePeople learn basic robotics by constructing sensor, action, and operator blocks with roBlocks (now Cubelets). [5] It also encourages players to experiment with different blocks and build modular structures.

Cubement is a mechanical movement design tool set with seven cubes: motor, bevel gear, gearbox, crank, jumper, breadboard, and support cubes. Users may rapidly master the foundations of mechanics by creating various mechanical systems. Whereas these varied kits allow users to build ideas, Cube-in offers a more basic pre-built kit in which users may play, observe, and learn about basic electronics concepts through easy interaction. Although simpler, Cube-in shares the ethos of various earlier tactile learning kits. [3]

Little Bits is a previous work that provides a tactile interface for youngsters to understand electronic circuit fundamentals. Through connections and modules, Little Bits seeks to provide a simple introduction to electronics. It is made up of modules that click together with magnets. Modules might be as basic as LEDs or as complicated as timeout modules, which allow users to specify timers inside their circuits. Little Bits reduces the need to be concerned about common mistakes that students make, such as polarity. However, because circuit components are given at a high degree of abstraction, with circuitry buried behind module components, it is ineffective for teaching lower-level ideas. [3]

Friedrich Froebel's thoughts on children's play and learning have changed education since the early nineteenth century. Froebel created a series of objects known as "Gifts," with the potential to link actual things to everyday children's play.

PhysicalPapert's work on Mindstorms was related to programming objects. As a result of Papert's constructionism theories, many programming languages have been created aimed at children. Initially, these programming languages were based on text or graphical user interfaces (GUIs). Text-based techniques need essentially rigid syntax and names of commands. On the contrary, graphical techniques were more adaptable, allowing youngsters to participate.to construct programming structures by dragging and linking symbolic representations on a screen computer monitor using the keyboard and mouse. [1]

A tool called Time-Me uses physical objects to depict time concerning daily activities. The device assists kids by internalizing and contextualizing time based on routine tasks.. [6]. Algorithmic Bricks (A-Bricks) were created to enhance the programming language experience by considering and exploiting procedural language characteristics. Algorithmic blocks were used to teach programming basics such as selection repetition. [7]Participants interacted in pairs with three distinct interface designs for a jigsaw puzzle: a physical (conventional), a graphical, and a tactile one. Exploratory research of kids completing a spatial puzzle assignment and examining how the advantages of tactile, visual, and physical interfaces may aid in developing thinking abilities. [8].MagicBuns are interactive items. This study aimed to investigate how various combinations of concrete feedback supported various play behaviors and kinds of play connected to various child developmental stages. Furthermore, a study of play behavior between kids between the ages of four and six and those between ten and twelve was done. They were establishing principles for building playthings that can develop with the kids. [9]. An inventive tangible user interface (TUI) design concept has been proposed for a manipulative digital drawing pen. The user interfaces for kids between the ages of 4 and 7 are based on interviews with focus groups, expert brainstorming sessions, and field survey findings. Children could use the new tangible user interface to select between the brush tools by touching and feeling the various patterns. By altering the tilt angle, the brush's thickness can be changed. [10]Early experiences with the physical environment can influence how a kid develops mathematical concepts. As a result, current studies on tangible interaction concentrate on preschoolers' formal (symbolic), or numerical understanding, of mathematics. Recent research on development, however, emphasizes the significance of working principle number representation in math learning. [11]

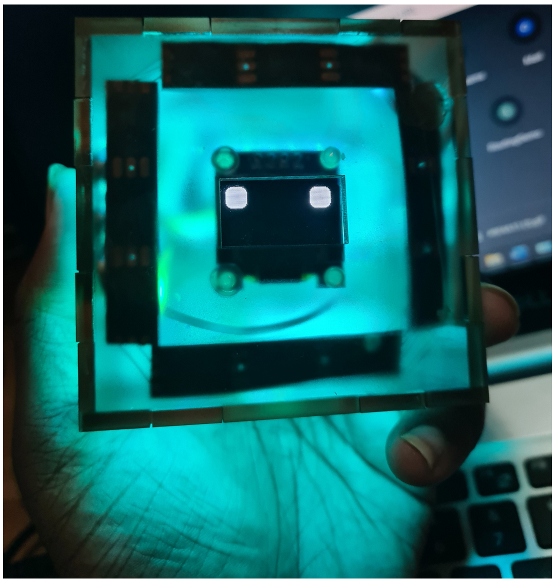

Fig. 1. Prtotyped TangiCube

III. Methodology

TangiGuru is the main component of the modern tangible e-Learning solution for early childhood development, which combines modern technologies such as cloud computing and embedded systems with traditional tangible learning solutions. These technologies enable the assignment of the TangiCubes for various teaching activities dynamically. Rather than the conventional tangible learning solutions, which are ready-made for one or a few specific learning activities, the dynamic nature of TangiCubes allows the users to use it for learning using a technically unlimited number of different learning activities.

A. TangibleCubes(Interaction Layer)

According to the Figure:2, different layers will support the TangiGuru to work together to aid the children in their learning activities.

The interaction layer consists of the developed set of TangiCubes which rely on the e-learning platform. TangiCube is a physical cube that is digitally augmented. It is created using acrylic sheets to give the children a look and feel of an actual cuboid shape. The other reason for selecting the cuboid shape is that it allows the children to connect and perform more activities together. The OLED display is the primary interaction interface in the cube. It can show the humanoid interface and the text-based outputs to perform the activities that will come from the TangiGuru application, which will be a software-based solution. The RGB addressable LEDs can deliver the different color combinations to the cube. The haptic feedback module can deliver feedback to the children. The accelerometer and the gyroscope can detect the motion of the cubes. The magnetic sensors will identify the connections of the cubes. Fig. 3 shows the opened cube with the integrated

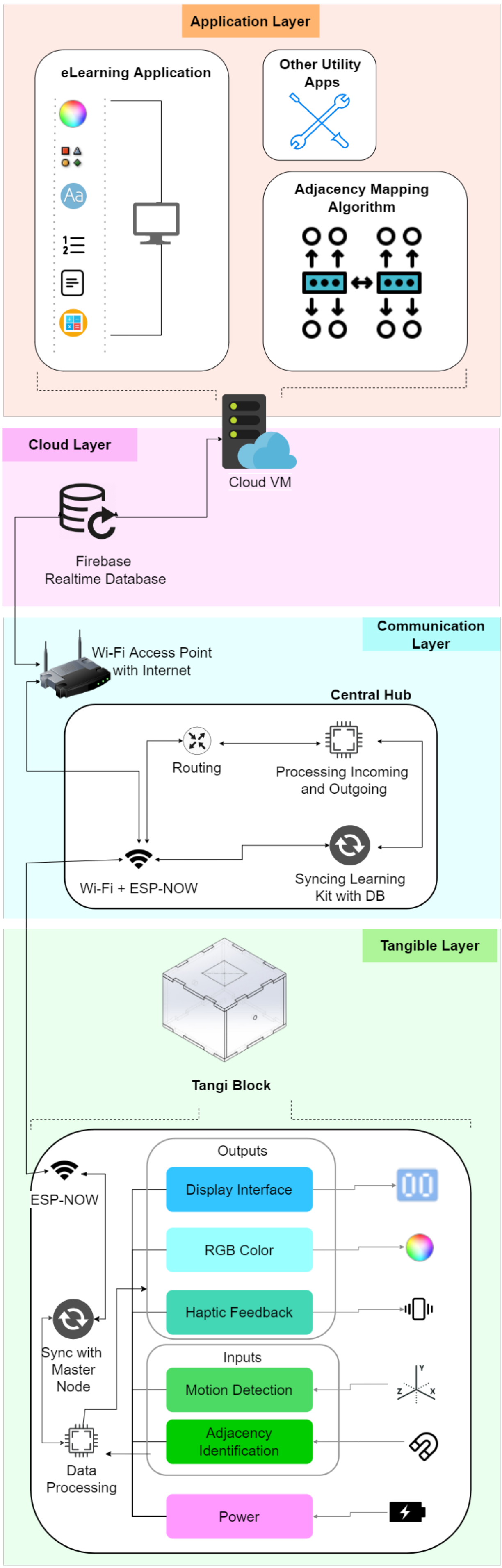

Fig. 2. System Overview

hardware. On the right-hand part, the whole assembled cube can be seen, which can be used to perform the activities with the application software.

TangiCube is an excellent platform for performing cognitive learning activities. These cubes can be connected or shaken to perform the activities. According to Figure. 1, different activities will be delivered via the e-Learning application hosted on the cloud environment. When a TangiCube is powered ON, it will give a humanoid interface on the OLED display to keep the children interacting with it. After that, it will be connected to the cloud-based backend via the central hub. The primary platform offers a variety of learning activity types, including multiple-choice questionnaires. The TangiGuru will offer two basic manipulations for TangiCubes to perform the learning activities correctly. In each activity, category answers can be given by shaking the cube or connecting the cube adjacently (placing next to each other, forming a row). If the activity category is a color-based activity, the RGB LED strip will offer the color the activity needs to display. If it is a letter, number, or shape activity, the corresponding letter, number, or shape will be displayed on the OLED display.

B. Communication (Communication Layer)

This function is responsible for interconnecting the virtual and physical counterparts of TangiGuru, which are manipulative TangiCubes and the e-Learning platform which hosts the cognitive learning activities. Interconnection of these components is done in three different levels as follows.

1) Software-level connection
2) Network-level connection
3) Tangible-level connection

All the software related to TangiGuru is hosted in a cloud environment. These software components include the e-Learning platform with learning activities, adjacency algorithm, and database. The adjacency algorithm is responsible for identifying the physical patterns of placements of TangiCubes in the real world. The e-Learning platform and the adjacency algorithm are hosted in a Linux virtual machine which is provisioned in an Azure cloud environment.

For the database, a real-time database management system is used. As the real-time DBMS, Google's Firebase Real-time Database is used as it comes with all the required features. Software-level connections are developed to meet the communication requirements among web UI, adjacency algorithm and database.

The user equipment of TangiGuru, the TangiGuru kit, consists of 12 TangiCubes and a central hub for communication. TangiCubes are working in a limited Small Area Network (SAN), which includes 12 of them and the central hub. The central hub manages the communication between the SAN and the cloud apart from the communication between the TangiCubes. These include routing data among tangible blocks, error checking and synchronizing the TangiGuru kit with the cloud-based backend. SAN uses ESP-NOW, a connectionless Wi-Fi communication protocol developed by Espressif. ESP-NOW squashes all the upper five layers of ISO-OSI 7 layers model into a single layer making it more simplified. This simplified nature of ESP-NOW is taken advantage of here for the miniature-size electronic hardware with lower specifications. So TangiCubes can communicate with the cloud-based backend with minimal processing power. This results in low power usage and minimal delay as these communications need to be delay sensitive because of the interactive nature of TangiGuru.

For the network-level connection, Wi-Fi is used since Wi-Fi can be considered the most widely used wireless internet access method in home and business environments. Here, Wi-Fi will connect the central hub to the Wi-Fi access point to provide internet access to the TangiGuru kit. Therefore, network-level connection interconnects the software-level and tangible-level of TangiGuru via the internet. Using Wi-Fi for internet connection allows the TangiGuru kit to connect to the cloud-based backend via the internet more efficiently than any other connectivity method while providing mobility to the kit and ease to use.

C. Child-Friendly User Interface (Application Layer)

An interactive, child-friendly user interface was developed for the e-Learning platform, which children can easily understand with interactive images and audio. The learning activities that come with the e-Learning platform are also designed to cater to this child-friendly user experience. When developing the user interface design for children, colors, font size, and font styles were considered. Especially color scheme is the primary visual guide for most of their activities, attracting attention and creating moods. Through this child-friendly user interface, children can perform different learning activities related to elementary mathematics ideas, color identification, similarity recognition, word building, and shapes. These outcomes develop the child's social, emotional, and physical development through these activities. After the activity, the performed activity will be evaluated automatically.

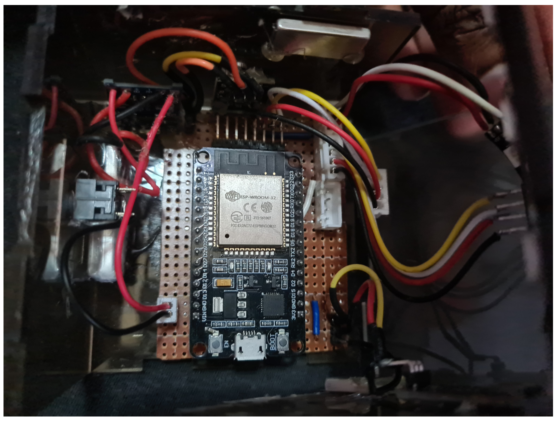

Fig. 3. Hardware Assembly

IV. Technology That Is Implemented

A. Hardware Architecture

The TangiCube is based on a simple architecture. It will be controlled with a low-power microcontroller with wireless capability and a set of sensors and actuators. The accelerometer can identify movement, and the orientation can be identified using the accelerometer and the gyroscope. The OLED display is connected to the controller using the I2C connection mode. The LED strip is also connected to the controller to a data line. Also, a vibration motor is connected to give children haptic feedback, which will be one of the main output methods to the users, according to the Fig. 3 The accelerometer, gyroscope used to implement the input methods. Also, IR Tx-Rx couples are implemented across tangibles to identify each tangible block by each other. A lithium polymer battery will power the whole system. Each cube will work as an individual system within the TangiGuru eco-system when performing the activities.

B. Communication

Three different technology combinations are used for the three communication levels found in TangiGuru implementation. Each of these levels works independently within itself. However, they only interact when data is transferred from one level to another.

1) Software-level communication: In software-level communication, all the communication is done among different software hosted within the cloud. These software components include hosting an e-Learning platform, database management system, tangible adjacency algorithm and other utility software, and communication. All these communications are done within the Linux Virtual Machine hosted in the Azure cloud. However, the database communications with the Firebase Real-time Database happen externally from the VM. This Real-time database instance is designed as the core of the data transfers among all the other components.

2) Network-level communication: Network-level communication is responsible for interconnecting TangiGuru Kit and the TangiGuru cloud-based real-time database. This component is designed to use Wi-Fi by allowing the TangiGuru kit to connect to a Wi-Fi network. Via the internet, the TangiGuru kit connects to the Firebase Real-time database hosted for the TangiGuru backend for communication between the TangiGuru kit and the TangiGuru e-Learning platform. The central hub in the TangiGuru kit connects the TangiGuru kit to its cloud-based backend as a whole. It utilizes its wireless antenna for connecting to the Wi-Fi network. Users are free to configure the designated Wi-Fi network at the startup of the TangiGuru kit by using the TangiGuru mobile app.

3) Tangible Level Communication: For tangibles-level communication, the same wireless radio in the central hub is utilized along with its Wi-Fi connectivity. An ESP32-WROOM32 series chipset is used as the processing unit of the central hub. Therefore, the ESP-NOW protocol is used as the communication protocol among tangibles for a low-power, fast wireless data transfer method. Tangible objects also use the same chipset, making it possible to create a Small Area Network (SAN) in ESP-NOW protocol within the TangiGuru kit. The firmware of the central hub is specially designed to optimize the usage of the wireless radio to reduce data loss when communicating in 2 different protocols with a Wi-Fi access point and 12 TangiCubes. A particular procedure is carried out at the startup of the TangiGuru kit to narrow down all the tangible blocks to the same Wi-Fi channel as the Wi-Fi access point. This procedure optimizes the utilization of wireless radio by allowing it to transmit and receive data in a narrow bandwidth. It avoids the slight delay of switching between different Wi-Fi channels for Wi-Fi and ESP-NOW communications.

C. Software

The e-Learning platform is a web application that is the graphical user interface that interacts with the child and allows choosing the activities that need to be performed. The software will give the instructions to the cubes based on the activity that is chosen. When a child performs the learning activity, the cube will evaluate the activity in real-time and show the results.

V. Technology Constraints and Opportunities

TangiCubes are equipped with an OLED display on one side. As a side effect of this, there was a problem with the orientation of the tangible. Therefore it was essential to ensure that the users place the TangiCubes in the upright position. The TangiCubes were designed to be a cuboid shape by reducing the height while keeping the width and the length equal. So, when the height is reduced, the child will have only two options: keep the side with the display on top, or keep the display side to the bottom. Because the display has a humanoid interface, it will always be on top. So, the confusion of having six sides equal will be solved for the users with the design.

VI. User and User Experience

The design process of TangiGuru has continuously been enhanced with feedback on what works and what does not from industry experts and intended users. In the prototyping phase, we created five learning activities for each category based on colors, shapes, numbers, and shapes. The application with the 3 TangiCubes was given to the children to play with the appliance. Interestingly, children were not concerned with the orientation of TangiCube, and it appeared normal to them. They realized what they had to do with the TangiCubes because the applications guide the child to perform an activity. With the finalized prototype, an informal user study was

Fig. 4. 6 Year Test Subject Performing the activities

carried out with the children because the work was ongoing. The prime goal of the study is to understand how children will handle the TangiCube with the application. We are interested in:

- What are the interfaces which make the cubes interesting?
- How the cognitive skills will be improved in the children?
- What makes the operations simple or challenging?
- The relationship with TangiCube, e-Learning platform, and the user experience.

VII. Results and Anlysis

The TangiCubes were initially tested with 27 children, and the time they took to part with TangiGuru was measured compared to a traditional tangible learning solution with their parent's consent. There were five 4-year-old children, seven 5-year-old children, seven 6-year-old children, and eight 7-year-old children. The study was done over two weeks, and each child was given unlimited time to play with a traditional tangible learning kit on a day of the first week. Similarly, each child was given unlimited time to play with TangiGuru on a day of the following week. The time taken by each child at each activity was calculated and analyzed.

Table I shows the average time the age groups interacted with a traditional tangible learning solution and the TangiGuru. The mean time of each age category shows how children interact with each solution. According to the values in the table, all children have shown more interest in TangiGuru by interacting with it more time compared to the traditional tangible learning kit. Notably, the interaction time for TangiGuru was almost double that of the traditional tangible learning kit.

TABLE I
Average Consecutive Time on a Traditional Tangible Learning Solution vs. TangiGuru

Age	**Traditional Solution**	**TangiGuru**
4 years	10.7 minutes	23.1 minutes
5 years	10.9 minutes	27.4 minutes
6 years	13 minutes	34.6 minutes
7 years	15.3 minutes	35.2 minutes

TABLE II
Average Time on the Controlled Interfaces

Age	**Humanoid Interface and Haptic Feedback disabled**	**Humanoid Interface disabled**	**Haptic Feedback disabled**
4 years	8.2 minutes	12.3 minutes	14.7 minutes
5 years	8.3 minutes	11.9 minutes	14.9 minutes
6 years	8.8 minutes	12.6 minutes	15.3 minutes
7 years	10.1 minutes	13 minutes	16.2 minutes

After that, the interactive parameters were controlled and tested again to measure the interaction time. The controlled parameters were the haptic feedback and the humanoid interface of the TangiCubes. According to Table II, first, both the parameters were turned off, and the evaluation was carried out. It showed that when both parameters were disabled, the interaction time was reduced to an average of 9 minutes. After that, the humanoid interface was disabled, and the haptic feedback was enabled. The average play time was increased to 12 minutes with the haptic feedback. When the haptic feedback was disabled, and the humanoid interface was enabled, the average playtime was increased to 15 minutes.

VIII. Conclusion

This study introduces a novel e-Learning appliance called TangiGuru, a tangible learning solution including 12 manipulative tangibles known as TangiCubes. Using the shape of a typical cuboid, we were able to implement a platform that will support children to do cognitive learning at their own pace. Using this solution, the children can improve their cognitive skills by manipulating the TangiCubes by connecting or shaking them. TangiGuru consists of various activities to perform with its own set of modernized tangibles, TangiCubes. The initial evaluation shows that having a different physical form and a different set of tangibles will prompt great engagement with the activities. Children will not consider the learning platform a traditional learning kit or a typical e-Learning application but rather identify it as an interactive toy. Therefore, TangiGuru can be used to teach children who will get distracted and lose interest quickly when performing the learning activities. They will be motivated to perform the activities more interactively. So this study can break the conventions of how a traditional computer uses to teach. The study confirmed that tangible objects could improve the interaction time compared to GUI applications. Also, the interface type will significantly impact the tangible objects.Regarding the limitations of this paper, TangiGuru cannot deliver tailored learning experiences for its users according to their learning patterns with itself. Therefore all the users experience the same no matter how excellent or poor the user is in learning. Other than that, even if TangiGuru can identify adjacent tangibles when placed together, this identification can only be made if tangibles are placed linearly. So this allows TangiGuru to evaluate word-making, sentence making and mathematical equation-solving skills. Still, TangiGuru cannot assess complex evaluations such as picture puzzles and scrabble-like activities.

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