Title	TaleTouch : building toolkits interactive toys for early STEM education
Sub Title	
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Publisher	慶應義塾大学大学院メディアデザイン研究科
Publication year	2025
Jtitle	
JaLC DOI	
Abstract	
Notes	修士学位論文. 2025年度メディアデザイン学 第1190号
Genre	Thesis or Dissertation
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO40001001-00002025-1190

Master's Thesis
Academic Year 2025

TaleTouch: Building Toolkits Interactive Toys for Early STEM Education

Keio University
Graduate School of Media Design

Xiling Shi

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

Xiling Shi

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Abstract of Master's Thesis of Academic Year 2025

TaleTouch: Building Toolkits Interactive Toys for Early STEM Education

Category: Design

Summary

This thesis explores conductive sponge as a safe and easy to use material to investigate the development of a modular, touch-responsive STEM educational toolkit for young kids. The study addresses the issue that the majority of STEM resources now available are made for older learners, which puts kids in kindergarten and early primary school students at a disadvantage. The toolbox prioritizes tactile interaction in order to assist emotional regulation, encourage active learning, and improve sensory engagement. The study uses a design-based research methodology to investigate how children's behavior, focus, and curiosity are affected by hands-on manipulation and instantaneous feedback (such as sound or light) in both controlled and unstructured play environments. Usability, patterns of engagement, and learning outcomes are revealed through field observations and interviews with kids and caregivers. By bridging the gap between exploratory play and fundamental STEM learning, the initiative hopes to provide a low-threshold, high-engagement educational solution.

Keywords:

STEM, children education, TUI, interaction, toolkit, creativity

Keio University Graduate School of Media Design

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Acknowledgements

I would like to sincerely thank Associate Professor Junichi Yamaoka and Associate Professor Donna Chen for their valuable guidance, feedback, and continuous support throughout my research.

Special thanks to the participating children and teachers whose cooperation made this research possible. I also extend my appreciation to my lab members for their support and inspiration.

Lastly, I would like to thank my friends for their unwavering encouragement and understanding during this journey.

Chapter 1
Introduction

In this thesis, STEM learning in early childhood is not approached as the transfer of formal knowledge, such as coding syntax or scientific facts. Instead, it is understood as an experiential and multisensory process where children begin to develop basic scientific thinking, engineering logic, and symbolic understanding through hands-on interaction.

Drawing inspiration from tinkering-based education and tangible media theory, this study explores how simple material actions—like pressing or combining conductive sponge modules—can elicit curiosity, prompt hypothesis-making (“What will happen if I press here?”), and foster intuitive cause-effect reasoning. These interactions are augmented by a responsive digital program, which delivers real-time audiovisual feedback.

The goal is not to “teach STEM” in the traditional sense, but to construct an environment where children can explore, observe reactions, build mental models, and express ideas—processes which are foundational to scientific and technical learning. This approach is especially important for preschool-aged children, whose learning is grounded in physical manipulation, emotional engagement, and symbolic play.

1.1. Early STEM Education Landscape

In recent years, the importance of early childhood STEM (Science, Technology, Engineering, and Mathematics) education has gained increasing recognition worldwide. This is particularly relevant in contexts like Japan, where shifts in national curriculum emphasize science and technology literacy from a young age. Research suggests that early engagement with STEM can have lasting impacts on children’s confidence, academic trajectories, and future career choices—especially in closing gender gaps in math and science participation [1].

As Brittany Bradford notes, early experiences in science and math are critical predictors of later success in STEM-related fields. [1]However, most existing research has focused on high school and higher education settings, with relatively limited attention to the foundational years of preschool and kindergarten. This highlights a pressing need to understand how early experiences can shape lifelong attitudes and abilities in STEM domains.

Canoy and Errabo further support this view by examining early childhood educators' beliefs and intentions toward STEM teaching. [2]They found that preschool teachers' confidence in delivering STEM content is strongly tied to their exposure to developmentally appropriate practices and their belief in the value of early hands-on learning. This reinforces the idea that early STEM education should not be viewed as "preparation for future learning" alone, but as a meaningful domain in its own right.

These perspectives emphasize that early STEM education must be grounded in concrete, embodied learning experiences rather than abstract instruction. Children need tools that allow them to manipulate, explore, and construct meaning through physical action. These insights form the foundation of the toolkit proposed in this study, which seeks to align age-appropriate STEM learning with multisensory and creative engagement.

1.2. Challenges for Young Learners

Despite the increased focus on STEM in early education, preschool-aged children are still unable to access many toolkits and learning settings. Most instructional technologies, from electronics kits to coding platforms, are made for kids 8 years old and up and rely on screen-based interfaces, fine motor skills, and logical thinking. These assumptions do not align with the developmental profiles of younger learners, who require hands-on, concrete experiences to construct knowledge.

Canoy and Errabo [2] indicate that inappropriate materials or highly abstract content are the main causes of young children's difficulties with STEM tasks, not a lack of interest. In order to maintain motivation and promote understanding, their research highlights the value of learning resources that incorporate tactile exploration, sensory interaction, and teacher support. In this stage of development, play, movement, and emotional expression are not just supplements to learning—they are core learning modalities.

Furthermore, research on technology-enhanced STEM education indicates that screen-based interactions could add to cognitive load, especially for kids who are still developing their ability to focus or control their emotions [3]. Although coding apps and tablets might be useful for older students, they frequently presume abstract thought and symbolic literacy, which makes it difficult for younger users to get started.

When taking into consideration children that have emotional or developmental difficulties, the gap becomes even more noticeable. Many of the tools available today are not adaptable enough to meet the demands of different learning styles, nor do they provide the kind of sensory engagement that might help children who struggle with self-regulation or attention.

The toolkits presented in this study was created to achieve two specific objectives in light of these constraints: (1) reducing the technical and cognitive barriers that are commonly connected to STEM education, and (2) facilitating intuitive, sensory-based inquiry using modular, touchable components. This is aligned with the larger trend toward high-ceiling, low-threshold learning systems that let kids start out easily and develop via unstructured play.

1.3. Technological Solutions & Gaps

The use of technology in early childhood education has increased recently, giving children access to interactive applications, digital platforms, and programming tools like Micro:bit and Scratch.While these solutions have proven effective for elementary-aged learners and above, they often present developmental mismatches when applied to children aged 4 to 6. For preschoolers who are still developing fine motor control, literacy, and sustained attention, screen-based or symbol-driven platforms may impose a high cognitive load and fail to provide meaningful engagement [2] [3].

screen-based interaction, which frequently restricts embodied participation. Li

Yang [4] points out that although networked technologies make content accessible, they run the risk of overshadowing the benefits of tactile and physically based learning. The developmental needs of young children, who gain more from experiential, sensory-based learning, may not be met by this screen-dominated method.

Tangible User Interfaces (TUIs) have emerged as a promising middle ground, allowing children to manipulate real-world objects while receiving digital feedback. However, as discussed in Chapter 2, the majority of TUIs still have limited accessibility because of resolved form factors, complicated hardware, or abstract logic structures that are beyond the cognitive understanding of preschoolers.

Thus, a critical gap remains in the design of low-threshold, sensory-rich educational systems that:

- Provide immediate, emotionally engaging feedback;
- Support both structured (task-based) and unstructured (creative) play;
- Allow intuitive interaction through materials that are soft, safe, and modifiable by young hands.

This thesis addresses this gap by developing a hybrid tangible-digital toolkit using conductive sponge modules, specifically tailored for preschool learners. The system combines simple tactile actions (pressing, connecting) with dynamic digital feedback (sound, light, animation), allowing children to build cause-effect understanding while expressing creativity through personalized crafting.

In doing so, it repositions technology in early education not as a replacement for physical play, but as a bridge between sensorimotor learning and symbolic exploration.

1.4. Research Goal

This thesis aims to investigate how a tactile, modular STEM toolkit—based on conductive sponge—can enhance engagement, creativity, and emotional motivation among children aged 4 to 6. Specifically, it explores how tangible material properties, digital feedback mechanisms, and the role of teachers shape children's learning experiences. By conducting a series of iterative design workshops and behavioral observations, the study responds to four guiding research questions and contributes to the development of age-appropriate, inclusive, and emotionally supportive early STEM education tools.

1.5. Thesis Structure

This thesis is structured as follows:

- **Chapter 1** introduces the research background, challenges in early childhood STEM education, and outlines the research questions.
- **Chapter 2** reviews key literature related to early childhood learning theories, tangible user interfaces (TUI), and existing educational tools.
- **Chapter 3** describes the methodology and research framework.
- **Chapter 4** presents the design process and toolkit development.
- **Chapter 5** analyzes field observations from final workshops.
- **Chapter 6** discusses the findings, reflects on research questions, and proposes future directions.

Chapter 2
Background and relative works

2.1. Theoretical Foundation of Early STEM Education

Early STEM education draws upon theories of developmental psychology, notably Piaget's constructivism and Vygotsky's sociocultural theory. Piaget [5]emphasized that children actively build knowledge through hands-on experiences, which is foundational to the integration of tangible toolkits in early learning environments. According to his stages of cognitive development, children aged 4 to 6 are in the preoperational stage, where learning is driven by sensorimotor engagement and symbolic play rather than abstract reasoning.

Vygotsky [6]highlighted the role of social interaction and scaffolding in learning, noting that young children benefit most when supported within their "zone of proximal development." This insight supports the idea that educational toolkits should be designed to allow for adult or peer guidance, particularly in unfamiliar or open-ended tasks.

Research has also shown that early exposure to STEM fosters long-term interest and confidence in technical fields [7], especially when children are engaged through age-appropriate, play-based learning environments.

2.2. Tactile Learning and Multisensory Interaction

Young children learn most effectively when multiple senses are engaged. According to Montessori [8], tactile and sensory materials help children refine their perception and develop fine motor skills essential for later learning. More recent research supports this view: tactile learning promotes better memory retention and deeper cognitive processing, especially when paired with visual and auditory cues [9] [10].

In the toolkit described in this thesis, soft conductive sponge modules provide a tactile entry point, while digital animations and sound offer real-time feedback. This multisensory design not only supports different learning styles but also reinforces cause-effect understanding in young children—key to early STEM engagement.

This theoretical basis directly informs Chapter 5’ s analysis, where children’ s emotional responses to tactile and audiovisual feedback are shown to sustain motivation and support symbolic thinking.

2.3. Tangible User Interfaces (TUIs) in Education

Tangible User Interfaces (TUIs) bridge the physical and digital worlds, allowing children to manipulate real objects that interact with computational systems. According to Ishii and Ullmer [11], TUIs enhance intuitive interaction, especially for non-readers or pre-literate children. Studies such as Horn et al. [12] and Zuckerman et al. [13]further emphasize the value of TUIs in early childhood, noting their ability to externalize abstract concepts like flow, logic, and interaction.

TUIs are particularly effective in collaborative settings, as children can physically share, modify, and explain tangible objects. However, most TUIs still assume a degree of fine motor skill or symbolic recognition not fully developed in preschoolers. The toolkit proposed in this study adapts the TUI concept into a more age-appropriate form, emphasizing low-threshold entry and open-ended exploration.

This framework directly supports Chapter 4’ s design iterations, where the shift from puzzle-based tasks to soft, modular components enables more natural child-system interaction.

2.4. Gamification and Motivation in Learning

Tangible User Interfaces (TUIs), when combined with gamified design elements, have been shown to enhance children’ s engagement, motivation, and conceptual understanding in educational settings. By allowing physical manipulation of interactive components and providing real-time digital feedback, TUIs help externalize abstract concepts—such as circuit logic or computational flow—in ways that are intuitive and developmentally appropriate.

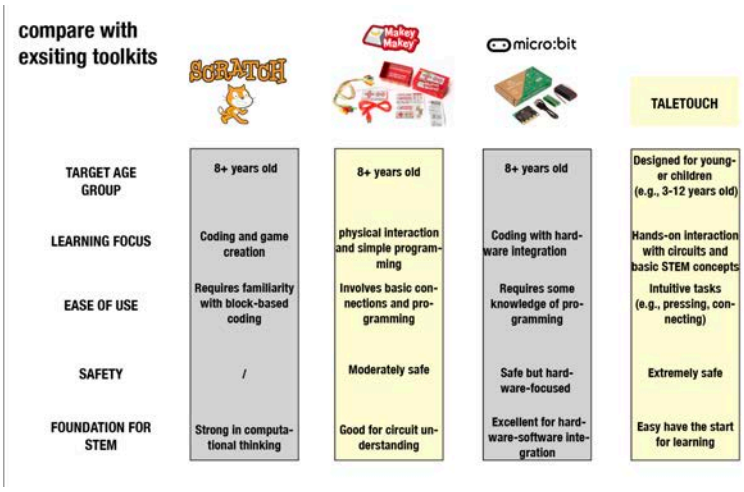
The SmartGame platform, a gamified tangible IoT system, demonstrated how such interfaces can support learning through hands-on, narrative-based, and personalized activities [14]. Its usability studies highlight improved learner attention, repeated engagement, and emotional investment—all critical outcomes for early STEM education.

While most gamified TUI systems have been explored with older children, prior studies have also extended such interfaces to younger or neurodiverse learners, indicating the broader accessibility and adaptability of this approach [13, 15]. This thesis demonstrates these principles through the design of Mode1 and Mode2 interactions (Chapter 4) and behavior observations (Chapter 5), where children’ s emotional expressions, repeated actions, and narrative play reflect the motivational impact of digital-physical feedback.

2.5. Existing Tools and Their Limitations

Over the past decade, a variety of educational toolkits—such as Scratch, Makey Makey, and Micro:bit—have been developed to promote children’ s engagement with STEM topics through coding, circuit building, and hardware-software integration. These toolkits have demonstrated clear success in supporting older children’ s learning, typically those aged 8 and above. However, they often present substantial barriers to younger learners, particularly children aged 3 to 6, who are still developing the cognitive, motor, and emotional foundations necessary for structured STEM tasks.

For instance, Scratch [16] requires users to engage in abstract thinking, sequence logic, and digital literacy through block-based programming. While this supports



(Sources: compiled by the author from the official websites of Scratch (`https://scratch.mit.edu`), Makey Makey (`https://makeymakey.com`), and micro:bit (`https://microbit.org`))

Figure 2.1 Comparing the existing toolkits

computational thinking, it assumes basic screen navigation skills, text-symbol recognition, and a longer attention span, which preschool-aged children are not yet developmentally prepared for. This results in high cognitive load, limiting accessibility for learners with emerging executive functions or emotional regulation challenges.

Makey Makey and Micro:bit offer more tangible interaction, but still require an understanding of electrical connections, symbolic mapping, and sometimes basic programming syntax. [16] [17] Moreover, these systems often follow task-driven learning models with expected outcomes, which may not align with younger children's exploratory and sensory-driven learning styles. In contrast to conventional STEM kits that emphasize coding accuracy or predefined engineering outcomes, the toolkit developed in this study—referred to as TaleTouch—was specifically designed to meet the needs of preschool-aged learners through a more intuitive, emotionally engaging approach. Rather than requiring prior technical knowledge or abstract reasoning skills, TaleTouch introduces STEM concepts through simple tactile actions such as pressing, connecting, and assembling soft conductive sponge components.

The name "TaleTouch" reflects the core idea of connecting touch-based interaction with storytelling and imagination. Instead of a static "patch," it emphasizes the sensory experience—how children physically engage with materials to build both circuits and narratives. This name captures the spirit of the toolkit: to foster playful discovery, sensory immersion, and symbolic expression, moving beyond task completion toward curiosity-driven learning.

By combining physical interaction with real-time audiovisual feedback and supporting both guided and open-ended activities, TaleTouch lowers the cognitive and emotional barriers often faced by younger or neurodiverse learners. Its soft, modular design ensures safe handling while accommodating a broad range of developmental stages. This approach positions TaleTouch not only as a STEM education tool, but also as an inclusive and developmentally appropriate platform for fostering creativity, exploration, and early scientific thinking.

2.6. Toolkit for Early Childhood Use

As discussed in the previous section, many existing STEM tools like Scratch, micro:bit, or Makey Makey are made for children who can already read or understand simple programming. [18] [17] These tools are helpful for older students but are not easy for preschool-aged children to use. Younger learners often don' t yet have the reading ability, motor control, or logical thinking skills needed to fully enjoy or learn from these platforms [12] Even tools that try to be beginner-friendly can feel too abstract or difficult, especially for children with emotional or behavioral barriers, or those who need more hands-on and sensory-based learning.

In contrast, the toolkit developed in this study was made especially for children aged 4 to 6. It uses soft, safe materials like conductive sponge, which are easy to touch, hold, and connect. The toolkit is built around simple actions such as pressing or joining parts, and children receive instant feedback through lights or sounds. This helps them stay engaged and understand the connection between their actions and what happens on the screen. This approach follows the idea of *developmentally appropriate practice (DAP)*, which means matching learning tools to children' s age, needs, and ways of playing [19, 20].

The toolkit allows for both free play and guided tasks. Its modular design makes it flexible, and its soft materials make it very safe—even for very young children. It gives children a way to explore basic STEM concepts using their hands and senses, rather than only looking at a screen or following complex instructions. In the next chapter, I explain how this toolkit was developed step by step, how it was used in real classrooms, and how it was improved based on children's and teachers' feedback. Such hands-on learning experiences, when grounded in real-life connections through STEM content, tend to be more effective and enjoyable. They not only increase engagement and interactivity but also offer multiple developmental benefits for young children. [3]

Chapter 3
Methodology

This chapter outlines the methodological approach designed to answer the three research questions introduced in Chapter 1. Each component—from the observational foundation to the toolkit's material design and evaluation strategies—was structured to explore (1) how tactile and modular tools enhance engagement, (2) what types of creative or emotional responses are elicited, and (3) how different play formats benefit from sensory feedback mechanisms.

3.1. Research Context and Exploratory Observations

The integration of interactivity into physical materials has been highlighted as a key strategy for enhancing early childhood education. As children' s toys are increasingly equipped with interactive technology, they can respond to children' s play in ways that support and facilitate learning. "Embedding interactivity into physical objects," according to Revelle et al. [21] , "allows the 'best of both worlds' -supporting traditional exploratory play with physical objects that can be extended and enhanced by the interactive power of digital technology." This design philosophy underpins the use of conductive sponge modules in this study, which allow children to explore logic and cause-effect relationships through physical assembly and real-time feedback.

Tangible User Interfaces (TUIs), as defined by Ishii and Ullmer [11], seek to bridge the digital and physical worlds by coupling digital information with physical objects. TUIs emphasize direct manipulation, spatial interaction, and the embodiment of data, making them particularly suitable for young children, whose cognitive and motor skills are still developing. Previous research (e.g., [12]) has demonstrated that TUI-based systems not only support children’ s engagement and motivation but also foster collaborative learning, conceptual understanding, and exploratory play.

Recent studies have reinforced the pedagogical significance of tangibility in multimedia learning environments for preschoolers. For example, Yilmaz [22]. argue that the absence of tangible elements in early digital learning systems often leads to limited engagement and superficial interactions. They emphasize that *tangibility fosters embodied cognition*, enabling young learners to better internalize abstract concepts through physical manipulation.

Similarly, in a case study titled *Making Digital Objects Tangible*, Alper [23] demonstrated that preschool children showed greater concentration and learning depth when using tangible tools compared to screen-only interfaces. Tangible media encouraged not only *sensorimotor coordination* but also spontaneous symbolic play and narrative construction—an essential form of expression at this developmental stage [23].

These findings strongly support the design direction of this study. The conductive sponge modules and modular toolkit used here are meant to serve as physically manipulable, feedback-responsive materials that allow children to explore logical operations, cause-effect relationships, and creative agency. The goal is to *merge the intuitive nature of touch-based learning with real-time digital feedback*, providing a hybrid interaction system that is cognitively stimulating and emotionally rewarding.

To better understand the natural learning context and current crafting experiences of children, preliminary observations were conducted at Green Port Sakuragicho Nursery (yokohama・Sakuragicho). The research team documented a 5-year-old class during a one-hour unstructured crafting session using recycled materials such as milk cartons and foam boards. Teachers provided minimal instruction beyond safety guidelines, and children were free to explore and create without a set theme. This observational fieldwork revealed several key insights:

- Many children maintained concentration for the first 15-30 minutes, with some engaging deeply in drawing, cutting, and storytelling. - Peer interaction and self-directed actions (e.g., ”I’m making a Pokémon computer”) emerged organically, highlighting the importance of materials that inspire symbolic play and narrative thinking.

This naturalistic observation informed the toolkit design process, revealing how open-ended materials and minimal teacher interference enabled children to pursue creative goals with intrinsic motivation. It also pointed to gaps in current practices—for example, the lack of structured opportunities to connect physical manipulation with computational or STEM-related thinking.

These observations and informal interviews with educators also revealed that while STEM activities are not formally implemented in many early childhood settings, there is growing interest in integrating hands-on, curiosity-driven learning experiences. Teachers valued safety, usability, and enjoyment when considering educational materials and emphasized the potential of modular, responsive components that support both guided and exploratory play.

The findings from these preliminary investigations directly shaped the development of the tactile, modular toolkit presented in this study. This toolkit is grounded in three interconnected goals: (1) to introduce basic STEM concepts through hands-on interaction with TUI components, (2) to provide emotional and sensory feedback through sound and light in response to children' s actions, and (3) to encourage both structured learning tasks and open-ended creative play.

3.2. Observational Background and Research Relevance

The Design-Based Research (DBR) methodology was used in this study to convert the results of the preliminary exploratory observations into an executable design. Because it combines iterative design, real-world testing, and theory-building in actual learning environments, DBR is especially well-suited for educational innovation. DBR ensures that the final products are developmentally appropriate, practical, and responsive to contextual needs by grounding the design process in authentic classroom behaviors and educator insights [24, 25].

A 60-minute open-ended craft project with recycled materials was seen during preliminary fieldwork at Green Port Sakuragicho Nursery in Yokohama. With supplies like milk boxes, foam sheets, and markers, kids were free to create without any set objectives or predetermined guidelines. Teachers used a low-intervention strategy, providing simple safety instructions and soft phrases like ”Take your time and go at your own pace.”

Although a lot of kids were excited at first, observational data showed that after the first 15 to twenty minutes, their interest frequently waned. The crafting process occasionally grew aimless in the absence of specific objectives or interactive results. A number of kids showed symptoms of disinterest, such starting irrelevant discussions or getting up from their seats. One child’s sudden question, ”Has anyone ever had potato chips?” during the lesson, for example, indicated a lack of concentration. Even while some kids kept drawing or embellishing their creations, their probability of paying attention for extended periods of time and engaging in meaningful investigation were restricted by the absence of cause-and-effect feedback.

While open-ended play is crucial for encouraging creativity, these patterns suggested a crucial realization: deeper engagement in STEM-related tasks may be hampered by the lack of response contact. The choice to include modular construction structures and sensory feedback systems in the toolkit design was influenced by this discovery. The updated design sought to create a more logical relationship between the child’s activities and the ensuing digital or physical response, as opposed to only depending on material freedom.

During this phase, teachers also offered insightful feedback, observing that children were particularly drawn to vibrant decorations, shapes resembling animals, and narrative components in their works. These choices helped create a prototype that could handle both planned and unplanned play by being included into later design iterations.

This study made sure that the prototype addressed both the theoretical STEM learning objectives and the real-world nature of early childhood play by integrating the design direction with observations from actual classrooms.

3.3. Materials and Prototyping Tools

Selecting materials for a STEM-based toolbox for young children involves considerations of safety, developmental appropriateness, and sensory engagement in addition to function. This project makes use of a tactile, modular toolset made mostly of flexible decorations, basic foam, and conductive sponge. These resources were chosen to foster immediate sensory feedback, open-ended creativity, and intuitive interaction—all of which are critical components for students in the 4-6 age range.

3.3.1 Conductive Sponge as Soft Interface

The main interactive component is the conductive sponge. Preschoolers' small hands are capable of handling it because it is soft and compressible. The physical and mental barrier of entry is reduced by conductive sponge, which enables freeform molding and squeezing in contrast to rigid electronic components present in commercial products like LEGO SPIKE or Arduino-based systems. The use of soft, deformable materials in early childhood environments has been supported by prior research in tangible user interfaces (TUIs), which improves motor engagement, attention, and affordance perception.

Additionally, the toolkit is scalable and practical for classroom application due to the affordability and robustness of sponge components. The tangible feedback in our toolkit to strengthen children' s engagement and causal reasoning.

3.3.2 Modular System

The "hamburger" shape of the toolbox consists of two layers of conductive sponge encasing a soft, non-conductive sponge that is secured with rubber bands. Children may design their own interactive controllers with this modular component. The sponge closes a circuit when it is squeezed, causing the screen to display audio or visual feedback (such as transformation animations, sounds, or jumping characters). This is consistent with studies demonstrating that children's motivation, exploratory behavior, and emotional involvement are all increased when they get real-time feedback during educational play.

The sponge toolkit uses body movement and sensory integration to assist youngsters develop intuitive understandings of cause-and-effect linkages, in contrast to many screen-only learning apps that place heavy cognitive demands on nonliterate users. [26]This also addresses criticisms about touchscreen learning in preschool, which, if not combined with tactile interaction, might shorten attention spans and impair symbolic reasoning. [27] [28]

Interaction Modes: Mode1 and Mode2

To support both individual exploration and social interaction, the toolkit was designed with two distinct interaction modes:

Mode1 allows for solo interaction. Children activate visual or audio feedback by pressing a single conductive sponge module connected to the Arduino. This direct feedback mechanism supports intuitive cause-effect learning and is especially accessible for younger participants who benefit from individual control.

Mode2 requires cooperation between two participants. Each child holds a separate sponge controller, and feedback is triggered only when the modules are brought into contact or rubbed together. This setup encourages collaborative play, turn-taking, and joint attention, aligning with Vygotsky' s theory of socially mediated learning.

These modes not only diversify the interaction experience but also provide developmentally appropriate scaffolds—starting from individual confidence building in Mode1 to peer-driven creativity in Mode2. (see figure5.6)

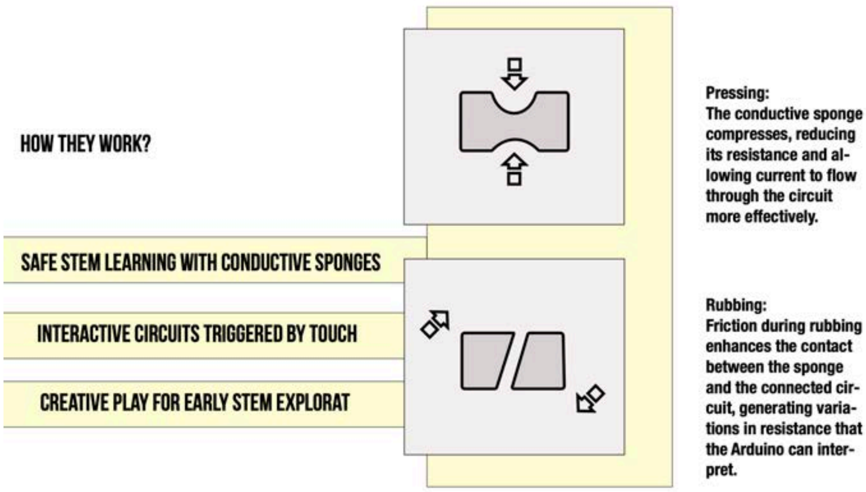


Figure 3.1 The principle of pressing and rubbing.

3.3.3 Comparison with Related Modular Systems

This part focuses more specifically on modular interaction mechanisms, whereas Chapter 2.5 examined a wide range of current STEM toolkits for kids, such as LEGO Education, clay kits, and Arduino-based systems, from the standpoints of age compatibility, usability, and developmental fit. This toolkit prioritizes open-ended, tactile-based engagement with instantaneous sensory feedback, in contrast to commercial products that frequently rely on predetermined components or call for literacy and programming skills.

Compared to SmartGame, this system offers:

- **Higher customization and flexibility**, as parts can be freely cut and assembled.
- **Age-appropriate tactile feedback**, aligning with preschool developmental stages.
- **Lower cost and fewer cognitive demands**, requiring no screen navigation or programming.

3.3.4 Transition to Workshop Implementation

The selection of soft, modular, and sensory-responsive materials has been explained in this section. Through tactile play, children may investigate cause-effect relationships in a STEM context thanks to the conductive sponge's safe and entertaining medium. In the next chapter, we look at how these materials were used in an actual workshop, how the kids reacted to them, and what types of emotional and creative engagement were shown.

3.4. Purpose and Theoretical Basis

A quick observation survey and interview guide was created for kindergarten teachers in order to assess how children between the ages of 4 and 6 demonstrate creativity during STEM-based activities utilizing a tactile, modular toolkit constructed from conductive sponge. These teachers were in a good position to spot minor indications of creative behavior and emotional engagement throughout the workshop since they were familiar with the kids' daily actions and social traits.

This evaluation tool's framework was informed by Nelson and Rawlings' *Experience of Creativity Questionnaire (ECQ)* [29]. Using dimensions like *Absorption*, *Power/Pleasure*, and *Clarity/Preparation*, the ECQ views creativity as a multifaceted experiential construct. These variables provide a complex method of evaluating creative involvement since they capture both internal emotional states and observable actions. The ECQ offered a useful conceptual basis for extending the observation of creativity to early childhood education, despite its initial intended for adult creative professions.

A supplementary framework was also provided by Kaufman and Beghetto's *Four C Model of Creativity* [30]. The idea of *Mini-C Creativity*—which is characterized as impromptu, personally significant ideas that arise during learning—was particularly pertinent. Mini-C is suitable for young children, whose artistic creations are best interpreted in light of their developmental stage and social surroundings. Instructors were asked to record examples of Mini-C creative behaviors, such as inventiveness, problem-solving, and persistent experimenting.

The assessment additionally integrated perspectives from Russ's studies on the symbolic and affective aspects of play [31]. Affective responses, symbolic material use, and receptivity to sensory feedback (such as the toolkit's sound or visual cues) were important markers. These components are commonly acknowledged as markers of prolonged cognitive attention and creative inspiration.

To sum up, the creativity observation tool integrated many well-known psychological frameworks, including Mini-C theory, ECQ, and affective play theory, to provide a field-ready and developmentally appropriate way to evaluate creativity in early childhood STEM activities. This method combined direct behavioral observation, teacher insights, and kid feedback to enable a triangulated analysis.

After introducing the workshop's framework and interactive toolkit features, the following section examines how the kids interacted with the various elements. To pinpoint certain creative expression patterns and the function of sensory feedback in fostering inquiry and participation, observational and interview data were analyzed.

3.4.1 Data Collection Procedures

A multimodal data collecting technique was used, combining post-activity interviews, instructor observations, and video documentation, to record the children's behavioral and emotional reactions during the workshop.

In keeping with the kindergarten's typical craft activity schedule, the workshop lasted roughly 90 minutes. This preserved ecological validity and made sure the session aligned with the kids' daily habits.

To record the entire class, a covert GoPro camera was placed in the classroom. The main purpose of the video was to examine how the kids interacted with the toolkit, physically moved the modules, behaved in an exploratory manner, and responded to light and auditory cues. To find trends of creative engagement, particular instances—like surprise, perseverance, or teamwork—were carefully examined.

Kindergarten teachers observed the children's reactions and provided help for classroom management at the same time. They were instructed to record instances of unexpected behavior, problem-solving skills, or emotional engagement. Open-ended written notes were used to record observations, and follow-up interviews were done very away following the session to get new perspectives and contextual explanations of the kids' behavior.

A modified template based on the theoretical dimensions—Absorption, Mini-C creativity, and Affective Reaction—discussed in Section 3.4.1 was given to teachers to help them with their observations. Teachers were able to reflect on times they felt were significant or suggest deeper engagement because the form allowed for unrestricted description.

This method provided a thorough and context-sensitive dataset to assess creative behavior and engagement by enabling triangulation between video analysis, educator understanding, and the children's apparent responses during the activity.

3.5. Ethical Considerations

Since this study involves young children in educational environments, ages 4 to 6, ethical considerations are especially crucial. Prior written approval was obtained from the kindergartens and the guardians of the children for all observational activities. Guardians were made aware of the goal, procedures, and intended use of the data gathered, and participation was completely voluntary.

There was no recording of any personally identifiable information, including names, faces, or voices. To protect privacy, all images and video recordings were anonymised. Only with prior consent was children's work (such as sensor modules or created objects) recorded for research analysis. To reduce the possibility of identification, children's faces were either blurred or completely removed from images or recordings where they were included.

All information gathered was safely kept on password-protected servers that were only accessible by the research team in order to preserve the privacy of the participants. The information will be kept for a predetermined five years before being permanently erased.

Furthermore, the study made sure that its methodology was non-invasive by observing kids in their natural play settings free from performance pressure or coerced intervention. All interactions with conductive sponge kits and other experimental instruments were optional and considered free play. Children were not formally assessed or tested, and there was no system of rewards or penalties in place.

Before the fieldwork started, the Keio University KMD Ethical Review Committee examined and approved these ethical measures.

Chapter 4
Design Process and Iterative Development

This chapter documents the design process and iterative development of the conductive sponge-based interactive toolkit, grounded in the methodological framework of Design-Based Research (DBR). DBR emphasizes the dynamic and situated nature of design in real-world educational contexts, prioritizing continuous cycles of design, implementation, evaluation, and refinement [24, 25]. Unlike traditional controlled experiments, DBR acknowledges the complexity and unpredictability of authentic learning environments, allowing researchers to adaptively respond to emerging challenges and opportunities.

In this study, DBR served not only as a methodological foundation but also as an ethical compass for developing a play-based, multisensory, and developmentally appropriate system for early childhood STEM education. The design trajectory progressed through successive iterations—beginning with material explorations and conceptual framing, advancing through early workshops and pilot testing, and culminating in the final integrated system that combined tangible interaction with digital feedback.

This chapter traces the evolution of the toolkit, illustrating how each design iteration was shaped by empirical observation, feedback from children and educators, and theoretical insights from developmental psychology, tangible user interfaces (TUIs), and embodied learning. The iterative process ensured that the toolkit aligned closely with the needs, capabilities, and learning styles of children aged 4 to 6, while also accommodating the pedagogical goals of early childhood educators.

4.1. Initial Concept and Prototyping

Three important insights the value of play in early learning, the efficacy of tactile and multisensory interfaces, and the necessity of age-appropriate STEM education —intersected to form the conceptual basis of this project. The original objective was to develop a user-friendly and entertaining tool that may help close the gap between abstract technology ideas and the hands-on learning style that is characteristic of youngsters between the ages of 4 to 6. [32] At this developmental stage, children learn most effectively through physical manipulation, sensory exploration, and imaginative engagement.

4.1.1 Exploratory Stage: Shiodome Workshop

The first exploratory activity, titled *Recrafting Children's Musical Toys from Recycled Packaging Waste* (hereafter referred to as the Shiodome Workshop), marked a crucial starting point in the design process. Instead of introducing specific technological components or predetermined learning goals, the initial workshop aimed to observe how children—primarily aged 4 to 12, along with a few slightly older participants—engaged in open-ended, hands-on creation using familiar, everyday materials.

The workshop was held over two days—August 3 and 4, 2024—at the NTV Shiodome Summer school. On August 3, four time slots were offered, each accommodating eight participants per session. On August 4, three sessions were held, also limited to eight participants each, with entry managed through on-site distribution of participation tickets. Most children attended with a parent or guardian, who remained present throughout the activity. Children with sufficient motor skills carried out the activity independently, while younger participants received light assistance from their parents.

Each participant spent approximately 6-8 minutes crafting their own interactive toy during the session. Participants were invited to freely explore the use of conductive sponge and recycled packaging to craft their own interactive musical objects. This open-ended format allowed researchers to observe children's spontaneous design behaviors, material preferences, and attention span in a real-world setting, serving as an important foundation for subsequent iterations.

Figure 4.1 Shiodome Workshop preparation.

Children were encouraged to build their own sound-making toys using pre-made elements derived from common recyclable materials. A recycled plastic food bag that had been filled with a sponge and a little whistle was used to make each toy. When children pushed or pressed the bag, the soft sponge, which served as an air pump, made the whistle sound. This simple pneumatic gadget allowed children to directly experience the relationship between physical exertion and auditory input.

Kids were free to decorate the outside of the bags however they wanted. （see Figures 4.2）The activity's structured yet flexible nature offered valuable insights into how kids engage with partially open-ended jobs and how even a simple interactive mechanism can generate enjoyment when kids sense control over the result.

This conversation led to the following significant conclusions:

- Youngsters clearly preferred soft, pliable items, particularly sponges, because they were tactile and simple to work with.
- Their level of involvement improved and they were more likely to keep exploring when their bodily efforts created immediate sensory feedback, even if it was just a "squeak" or "rattle."

Figure 4.2 children craft their own interactive musical objects.

- The early development of symbolic thinking and narrative building is demonstrated by the large number of children who named their items, described their purposes, or made up stories about them.

This early workshop was instrumental in highlighting the creative potential of open-ended making. It demonstrated that giving children agency to design and personalize their artifacts—rather than guiding them through fixed tasks—led to deeper emotional investment and sustained attention. While the workshop did not involve circuitry or coding, it confirmed that soft materials and immediate feedback could form a strong foundation for introducing abstract STEM concepts through play.

These insights became a turning point in the design philosophy of the project. Instead of beginning with rigid logic-based tasks, the next design stage would explore how to embed structure gradually, while preserving the freedom and playfulness of the hands-on process that had proven so powerful in this initial setting.

4.1.2 Structured Interaction: Zoo Workshop -A Puzzle-Based Exploration of Tangible Circuits

Following the open-ended, craft-based experimentation of the Shiodome Workshop, the second iteration of the design took a more structured and goal-oriented approach, in order to test how young children would engage with puzzle-based,

Figure 4.3 Shiodome Workshop.

Figure 4.4 Shiodome Workshop.

circuit-completing tasks. This workshop, referred to as the *Zoo Workshop*, introduced children to modular animal-shaped kits made of laser-cut conductive sponge parts, with the aim of bridging tangible assembly with basic STEM logic. The Zoo Workshop was held on March 23, 2025, from 11:00 AM to 2:00 PM children aged around 3 to 8 years old, with the majority between 4 and 6. Each child was accompanied by at least one parent or guardian, who provided on-site assistance during the hands-on process. The presence of guardians offered additional scaffolding and ensured that even younger participants could fully engage with the puzzle-based task.

Each child was assigned a "mission": to complete an animal character (e.g., a turtle) by locating and assembling the correct conductive sponge pieces in a designated order. A custom-printed zine-style instruction booklet guided them through the process, using step-by-step illustrations and friendly language. For instance, in the turtle activity, the child was prompted to first find specific body parts, then place them one by one in their correct positions on a baseboard. When the final piece was placed, the full circuit was completed, triggering a small LED light embedded in the turtle’ s shell to illuminate–providing immediate visual feedback and a moment of accomplishment.

The electrical mechanism itself was simple but effective: each sponge piece functioned as part of a physical circuit, and only when all the correct components were connected in sequence did the soft switch close the loop to power the LED. This was a deliberate design choice to reinforce the idea that “every piece matters” an intuitive representation of how logical sequences or conditions work in circuits.

The workshop accommodated children of varying developmental stages by offering tiered levels of complexity:

- For younger children (ages 4–6), pre-cut conductive shapes were provided so they could focus on placing, pressing, and observing feedback.
- Slightly older participants were given additional freedom to cut the conductive sponge into custom shapes—such as animals or imaginary creatures—encouraging creativity and personalization while still working toward the core circuit completion task.

Children responded enthusiastically to the animal theme and recognizable shapes, showing excitement when the LED lit up and proudly announcing their turtle was "alive." Teachers noted that this type of meaningful content design (e.g., familiar animals) helped keep children engaged. Moreover, the use of soft, squeezable sponge materials once again proved highly suitable—offering a familiar tactile experience that was safe, comfortable, and easy to manipulate.

However, the workshop also revealed a critical challenge. Once the LED had turned on and the task was deemed "complete," many children quickly lost interest and moved on. Unlike the previous session, where children continued inventing stories or reconfiguring their creations, the clear goal-oriented structure limited opportunities for imaginative extension. The interaction became defined by a sense of "mission accomplished," rather than ongoing exploration.

This shift highlighted a design tension between task completion and creative agency. While the workshop successfully introduced tangible logic and reward-based learning, it also suggested that too rigid a structure may constrain narrative play and personal expression. As such, this workshop became a crucial reflection point in the project—raising the question of how to design systems that not only teach cause-effect relationships but also sustain children's curiosity, storytelling, and emotional engagement beyond the initial moment of success.

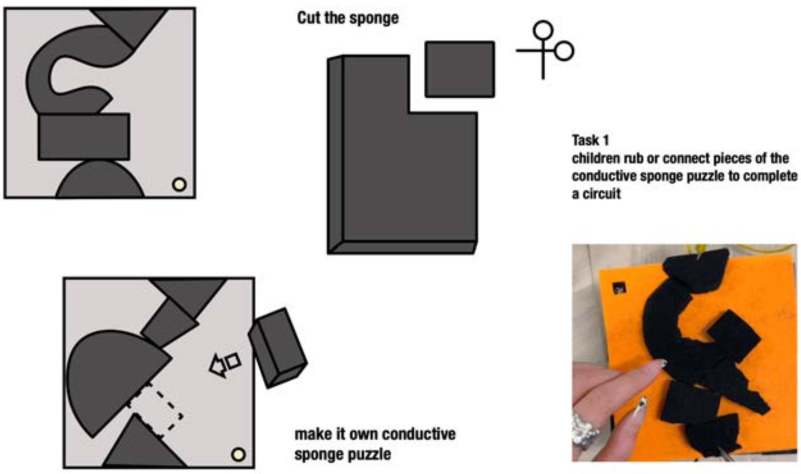


Figure 4.5 Children assembling puzzle-based conductive sponge kits in the Zoo Workshop.

Figure 4.6 Children interacting during the Zoo Workshop.

4.1.3 From Physical to Digital-Tangible Hybrid

Based on observations from the Zoo Workshop and teacher feedback, the project' s direction evolved once again—from a purely physical toolkit to an integrated physical-digital system. Teachers highlighted that while children enjoyed the tactile play, many lost interest when the feedback was too simple or repetitive. In response, screen-based visual and auditory elements were introduced using Processing, enriching the system' s narrative potential and supporting visual storytelling and symbolic interaction.

This iteration enabled the integration of animated characters, falling stars, interactive hearts, and a moonlight effect—features designed to stimulate emotional engagement and narrative-driven play. As noted by Alper et al. [23] and Liu et al. [33], digital-physical hybrid systems can help young children internalize abstract logic through multimodal feedback and imaginative immersion.

The Zoo Workshop showed that focused on tasks circuit completion might help youngsters grasp the fundamentals of electronic logic, but it also exposed a draw-

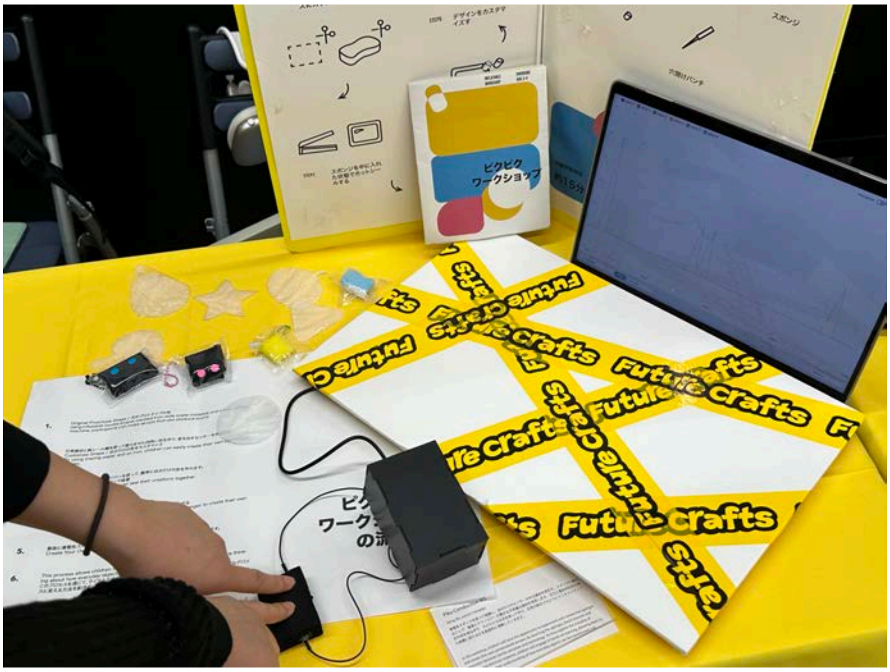


Figure 4.7 Zoo Workshop.

back: many kids soon lost interest in the provided puzzle after finishing it. On the other hand, previous exploratory workshops demonstrated that letting kids make their own designs led to deeper engagement. These results led to a significant change in the design philosophy, which became essential to further revisions of the toolkit. The design philosophy shifted from predetermined task completion to open-ended, child-driven creative interaction.

4.2. Material & Interaction Design

Designing a developmentally appropriate and engaging toolkit for children aged 4 to 6 required deliberate attention to both the physical properties of materials and the nature of interactions they afford. This section outlines the rationale behind the selection of conductive sponge as the core input medium, the design of tactile interactions tailored to young children's motor and cognitive abilities, and the integration of multisensory feedback to reinforce learning and motivation.

Material Selection: Conductive Sponge as a Tactile Interface

The primary interactive material used in the toolkit is conductive sponge, a soft and compressible material infused with conductive particles that can act as a switch when pressed or connected. Its physical properties make it highly suitable for young children: it is safe to touch, easy to grip, and invites playful manipulation. Compared to rigid components found in conventional STEM toys, the conductive sponge provides a low-barrier and intuitive way for children to engage with technology.

This choice is rooted in research on Tangible User Interfaces (TUI), which emphasizes the cognitive and embodied learning benefits of embedding computation in physical objects [11]. In addition, Yavuz and Veske [34] advocate for the use of soft, deformable materials in play-based learning, citing their ability to enhance tactile exploration, emotional comfort, and expressive interaction.

The sponge' s softness makes it particularly suitable for early childhood interaction, including use by children with limited fine motor control. Even participants slightly older than the core 4-6 age group showed sustained interest in manipulating sponge materials, indicating strong material versatility across developmental levels.

Tactile Interaction Design for Early Learners

Recognizing that touchscreen interfaces may impose cognitive and motor challenges for non-literate or younger children [27], this toolkit adopts gross motor tactile interactions as the primary input modality. Children interact with the system by pressing, squeezing, or connecting sponge modules. These simple physical actions are mapped directly to digital responses, allowing children to form clear mental models of cause-and-effect relationships.

Multisensory Feedback to Support Learning

To amplify engagement and reinforce learning outcomes, the toolkit integrates real-time multisensory feedback. When children interact with the conductive sponge modules, the Arduino microcontroller detects the input and transmits signals to a Processing-based program. This triggers visual effects—such as falling stars, animated characters, blinking moons—and corresponding audio responses including cheerful sound effects or voice prompts.

This coupling of physical action with audiovisual response supports not only motivation but also conceptual learning, such as understanding circuits, sequencing, or logical connections. According to Yilmaz et al. [22], such feedback loops improve retention and exploration in early learners. Similarly, Liu et al. [33] demonstrate that multimodal, tangible systems can foster confidence and emotional engagement even among children with learning challenges.

The toolkit thus transforms abstract ideas like "completing a circuit" into concrete, emotionally salient experiences, increasing both accessibility and relevance for young children.

Modularity and Creative Expression

Beyond task completion, the toolkit was also designed to foster open-ended creativity. Modules were intentionally made reconfigurable and non-prescriptive, allowing children to freely arrange, combine, or decorate sponge parts. In some sessions, older participants were encouraged to cut their own shapes, while younger ones selected from pre-cut templates. This blend of structure and freedom aligns with Papert' s constructionist theory [35], which advocates learning through making and self-directed discovery.

This open-endedness supports what Kaufman and Beghetto [30] define as Mini-C creativity—emergent and personally meaningful forms of creativity that are especially salient in early childhood. Rather than being restricted to "correct" outcomes, children could assign symbolic meaning to their creations—turning sponge modules into animals, characters, or imaginary tools-deepening emotional investment and storytelling potential.

4.3. Design workshop

To evaluate the feasibility, usability, and educational potential of the conductive sponge-based interactive toolkit, a full-cycle design workshop was conducted in an authentic early childhood education environment. This workshop represented the implementation and observation phase of the Design-Based Research (DBR) process [24], allowing researchers to assess how children engaged with the system in a realistic classroom context, and how teachers supported or mediated these interactions.

Workshop Site and Context

The design workshop was conducted at a partner kindergarten located in the Yokohama region. This site was selected to closely reflect children's everyday learning and play environment, thereby enhancing the ecological validity of the study. The classroom setup, familiar teacher-child relationships, and unstructured activity rhythms ensured that the children' s engagement with the toolkit could be observed in a naturalistic and developmentally appropriate context.

Participants

- **Children**: A total of 24 children aged 4 to 6 years participated in the workshop. This age range was chosen to align with the toolkit' s target users and to capture diverse developmental characteristics within the preschool stage. The participant group exhibited a range of motor, cognitive, and social skills, which provided valuable variability for assessing the toolkit' s adaptability and inclusivity.

- **Teachers**: Four teachers were actively involved during the sessions. To ensure age-appropriate support and observational consistency, children were grouped by age, with each group assigned one lead and one assistant teacher. All teachers were regular faculty at the kindergarten, deeply familiar with the children' s behavioral patterns and developmental profiles. Their presence ensured that observations were contextualized within each child' s normative classroom behavior, and that timely scaffolding could be provided where necessary.

Prior to the workshop, informed consent was obtained from both the kindergarten administration and all children' s guardians. Ethical procedures, including clear explanations of the research purpose, data handling, and privacy safeguards, were followed in accordance with institutional protocols (see Section 3.7).

Material Preparation and Differentiation

Recognizing the developmental diversity among preschoolers, the workshop employed a tiered material preparation strategy. Children were provided with conductive sponge components in two formats:

- Pre-cut animal and object shapes for immediate use by younger children (ages 4–6), minimizing cognitive load and motor challenges.(see Figures 4.8 and 4.9)
- Blank sponge sheets and safe scissors for older or more dexterous children, allowing for self-cutting, customization, and creative exploration.

This differentiation ensured that all children could participate meaningfully regardless of motor skill level, and allowed for both guided assembly and open-ended creation. Each module embedded conductive paths to enable circuit completion through physical contact or combination.

Interaction Design and Workshop Procedure

The workshop followed a four-phase structure:

1. **Introduction**
   Children were briefly introduced to the soft sponge components and shown how touching or combining them could trigger lights, sounds, or animated responses on the screen.
2. **Free Exploration**
   Participants were encouraged to experiment freely with assembling the sponge pieces, pressing or squeezing them, decorating shapes, or inventing new characters using stickers and markers.

Figure 4.8 Conductive sponge precut by laser cutter (1).

Figure 4.9 Conductive sponge precut by laser cutter (2).

3. **Interactive Play**
   Once a physical interaction was detected by the Arduino system, it triggered dynamic audiovisual feedback in Processing. These included falling stars, jumping characters, glowing hearts, and playful sound effects. The interactions were intentionally designed to be multisensory and emotionally engaging.

   Detailed effects included:

   - **Jumping:** When a child pressed the conductive sponge (Mode1), the on-screen character jumped upwards, providing a clear and satisfying response.
   - **Falling Stars + Obstacle:** Stars continuously fell from the top of the screen. When these stars collided with a black monster-like obstacle, a cheerful “ding” sound was triggered, surprising children and encouraging repeated experimentation.
   - **UFO Transformation:** In Mode2, if a child’ s character came into contact with a flying UFO after cooperative input, the character transformed into an astronaut. This unexpected visual transformation delighted children and often sparked storytelling.
   - **Heart Effects:** When two characters touched each other, a glowing heart briefly appeared, expressing emotional interaction between players.

   These symbolic and playful responses helped children link their physical actions with digital outcomes, reinforcing cause-and-effect understanding and sustaining their interest.

4. **Reflection and Observation**
   Teachers and researchers recorded children’s behavior, verbal responses, and level of engagement. Special attention was paid to how children collaborated, expressed emotional reactions, asked questions, or re-engaged with the toolkit after feedback events.

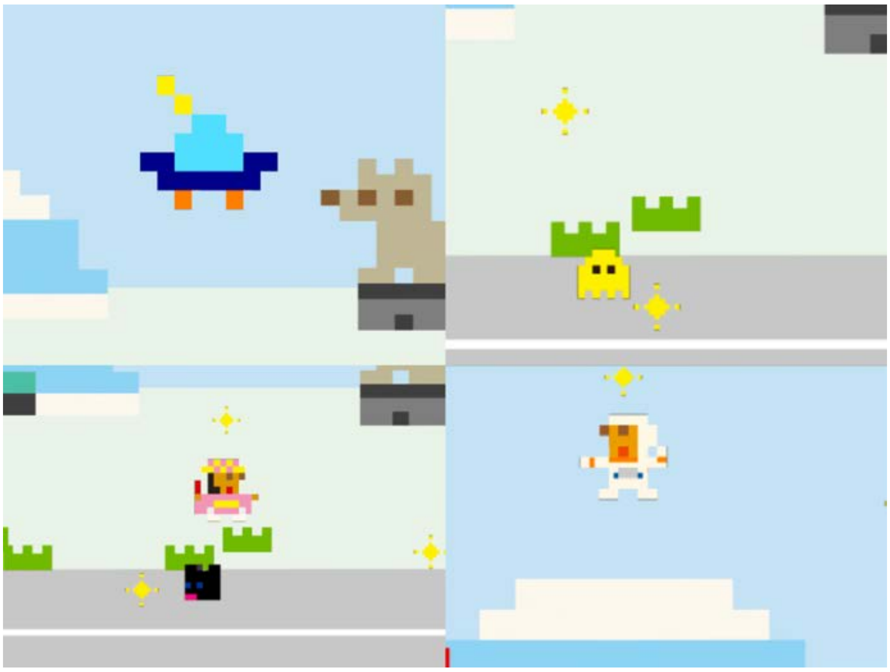


Figure 4.10 effects

This procedure was designed to balance task-based interaction (e.g., completing a connection) with open-ended creative play, in alignment with constructionist learning theory [35].

Final Interaction Modes and Processing Implementation

Building on the two basic interaction modes defined in early prototypes—**Mode1 (Pressing)** and **Mode2 (Rubbing)**—the final system was implemented using Processing in conjunction with Arduino to enable rich, responsive digital feedback based on children's physical interactions.

In **Mode1**, pressing the conductive sponge activated a series of visual effects in the Processing interface. For example, pressing would make the on-screen character jump, trigger the appearance of falling stars, or, when timed with the passing UFO, transform the character into an astronaut. These animations were designed to be both playful and symbolic, reinforcing cause-and-effect understanding through immediate sensory feedback.

In **Mode2**, when two children pressed their sponge controllers at the same time, the characters on screen began to move toward each other. Upon contact, they triggered special effects such as heart-shaped animations or a transformation event. This mode emphasized collaborative timing and emotional expression, promoting social interaction and shared play.

The system relied on two primary input functions—`pressing` and `rubbing`—mapped to different types of sensor behaviors (e.g., analog thresholds or dual input detection). Processing was used not only to receive real-time analog signals from Arduino but also to generate a game-like interactive environment with custom backgrounds, animated sprites, and sound effects.

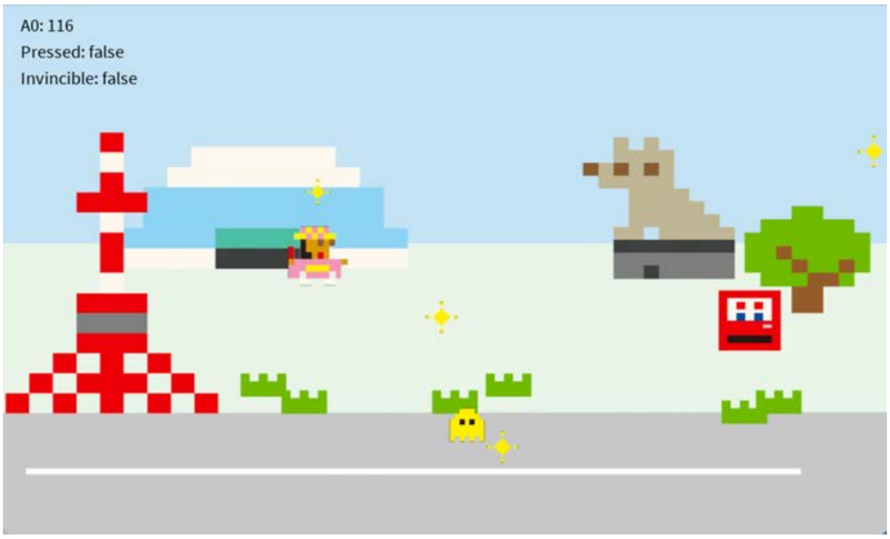


Figure 4.11 Processing animation example from Mode1: Pressing triggers character jump and UFO transformation.

These effects were not merely decorative—they served as key motivational elements in the workshop. Children were observed repeatedly pressing or coordinating with peers in order to see the animations, demonstrating emotional investment and a desire to explore the outcomes. As teachers noted, the combination of tactile input and animated response was essential to maintaining children's attention throughout the 90-minute session.

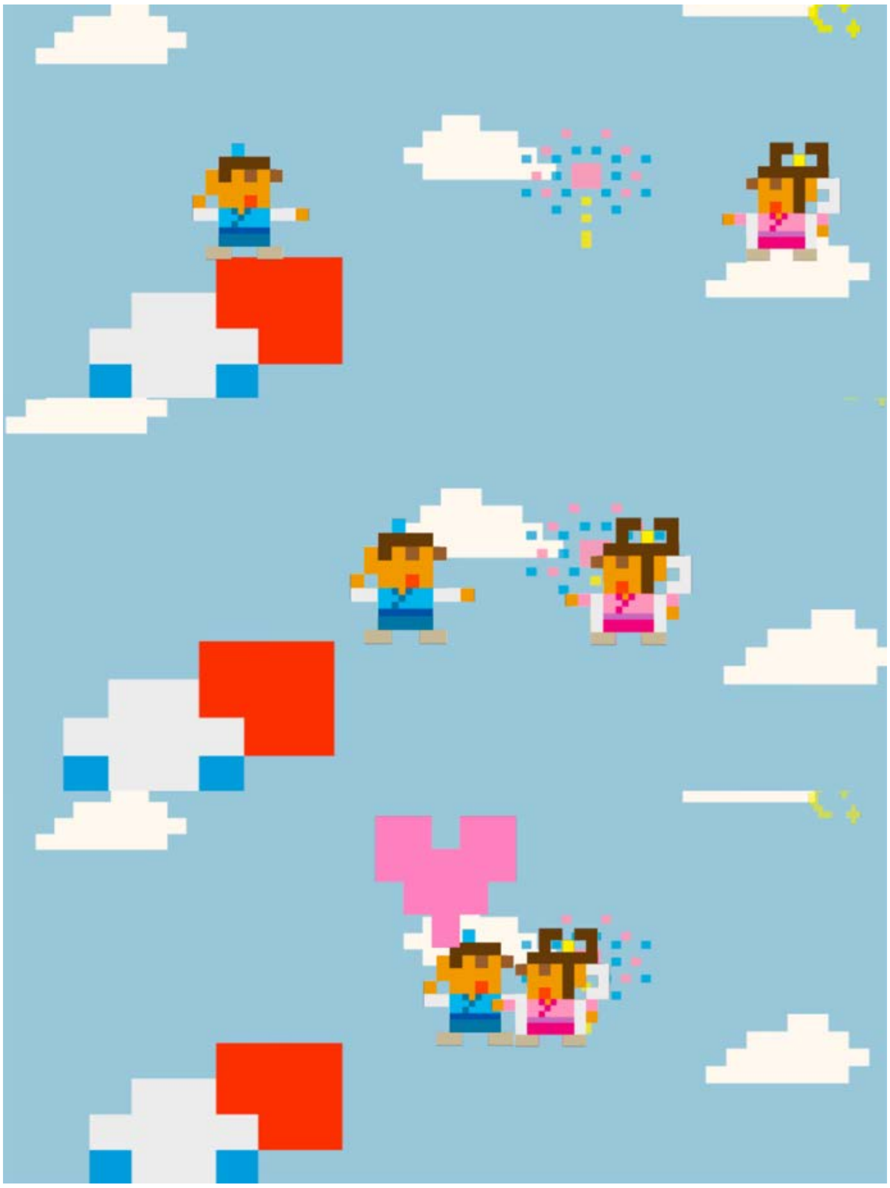


Figure 4.12 Processing animation example from Mode2: Two characters meet and trigger heart animation.

Role of Teachers and Observational Focus

Teachers played a non-directive but supportive role, acting as scaffolding agents [6] who occasionally posed guiding questions, narrated visible changes (e.g., “Look, the star moved!”), or encouraged peer interaction. Their presence helped create a safe and encouraging space while avoiding over-instruction.

Observation focused on the following key points:

- How quickly children understood the sponge interaction mechanics
- Whether multisensory feedback prompted curiosity or sustained attention
- Which shapes, triggers, or visual effects were most engaging
- How children interpreted feedback and adjusted their actions
- Instances of collaboration, imitation, or storytelling

These insights were essential in informing the next round of design iteration, particularly in fine-tuning visual feedback, adjusting trigger thresholds, and increasing opportunities for imaginative expression.

4.4. The Role of Teachers

The Role of Educators as Observers and Co-Designers

In the development of educational technologies for early childhood, educators play a critical role not only as facilitators of learning but also as invaluable observers and collaborators in the design process. Their deep understanding of children’ s everyday behavior, developmental trajectories, and classroom dynamics makes them indispensable stakeholders for any research aiming for ecological validity and real-world applicability.

During the workshops conducted at the partner kindergarten, insights were continuously gathered from the kindergarten teachers. This collective perspective, grounded in their daily interactions with the children and their broader pedagogical vision, enabled a nuanced understanding of observed behaviors—often extending beyond what could be captured by researchers alone. For instance, educators contextualized children’s responses by noting how temperament, attention span, or prior experiences influenced their interaction with materials or their reaction to feedback. Their unique observational capacity helped the research team interpret engagement patterns and emotional responses with greater pedagogical relevance, distinguishing between momentary novelty and sustained interest.

Beyond observation, educators also served as **scaffolding agents**, a role grounded in Vygotsky’s theory of the Zone of Proximal Development (ZPD) [6]. Rather than providing direct instruction, teachers gently guided exploration by asking open-ended questions, highlighting cause-effect relationships (e.g., “What happened when you squeezed the sponge?”), and fostering collaborative problem-solving. This approach preserved children’s autonomy while offering meaningful adult support.

Furthermore, consistent with the co-constructivist philosophy underpinning Tangible User Interfaces (TUIs), educators played a key role in shaping the learning narrative. The TUI system served as a shared platform for interaction, and teachers’ verbal prompts and responsive gestures helped children connect their physical actions with the abstract STEM concepts represented onscreen. This dynamic interplay between the child, the tangible toolkit, and the mediating adult illustrates how educators act as co-creators of meaning, supporting both immediate learning outcomes and long-term design refinement.

Figure 4.13 Examples of adult scaffolding during toolkit interaction.

4.5. Iterative Improvements

The Zoo Workshop served as an important validation of the toolkit's core concept—demonstrating that tangible circuit puzzles could help young children understand basic electronic logic. However, it also revealed several key limitations that necessitated further iteration. Observations and teacher feedback consistently pointed to a critical engagement drop-off: once the puzzle was completed and the LED light turned on, many children quickly lost interest. The activity, though effective at illustrating "cause and effect," lacked space for extended exploration, personalization, or storytelling.

From Fixed Puzzle Tasks to Creative Ownership

In response, the subsequent iteration introduced a shift in both interaction design and learning philosophy. Instead of asking children to complete a predefined character, they were now invited to create their own interactive controller or "soft robot" using conductive sponge. This soft, tactile material—already proven to be intuitive and enjoyable to manipulate—became not just the medium for input, but a canvas for expression.

Children were given blank sponge sheets and materials such as scissors, markers, and stickers. They could cut the sponge into any shape they liked—animals, imaginary creatures, or abstract forms—and decorate them freely. These personalized modules retained full conductive functionality and, when connected, would trigger custom screen-based feedback via Arduino and Processing.

This design pivot addressed the core limitation of the previous task-based setup: rather than completing a single solution, children were now engaged in an open-ended cycle of making, testing, observing, and storytelling. The act of creating "something I made myself" fostered deeper emotional investment, increased playtime, and stimulated symbolic thinking. Many children named their soft robots, assigned them personalities, and incorporated them into spontaneous narratives.

Improving Trigger Sensitivity for Young Children

Alongside this creative shift, the system's physical responsiveness was also refined to better accommodate the motor abilities of younger children. In the Zoo Workshop, some participants struggled to apply sufficient pressure to trigger feedback. To solve this:

- The mechanical connection inside the sponge module was optimized to allow activation under lighter force.
- The Arduino analog signal threshold on pin A0 was adjusted in the software to detect smaller changes in pressure, making the system more sensitive and responsive to subtle touch.

These improvements ensured that even children with limited grip strength could successfully interact with the toolkit—thus improving accessibility and inclusivity across developmental levels.

Layered Feedback for Sustained Engagement

The iteration also introduced multisensory and symbolic feedback to replace the one-time LED activation. Now, each child's interaction could trigger:

- Visual animations: falling stars, glowing hearts, blinking moons, animated characters
- Sound effects: cheerful tones, "completion" prompts, or playful cues tied to successful input

These feedback mechanisms served dual purposes: providing immediate confirmation of interaction, and stimulating emotional engagement and narrative potential. Unlike a binary light/no-light result, this layered response system created opportunities for continued experimentation, discovery, and imaginative elaboration.

Educational Impact and Iterative Insight

Together, these iterative improvements redefined the toolkit not as a set of circuit tasks to complete, but as a hybrid creative environment—where logic and expression could coexist. It reaffirmed one of the core tenets of Design-Based Research: that successful educational tools evolve not only through technical refinement, but through real-world feedback and contextual understanding (Barab & Squire, 2004).

By responding to what children actually did—and what teachers observed to matter—this design iteration transformed the toolkit into a more emotionally engaging, inclusive, and expressive system, better aligned with the learning needs and creative capacities of children aged 4 to 6.

Through these iterative improvements—from structured puzzle play to creative self-made controllers—the toolkit evolved into a hybrid learning space. While early activities confirmed the power of tactile feedback and playful interaction, the final version added narrative engagement, multisensory richness, and child-led creation. These changes made the system not just more interactive, but also more meaningful for children.

In summary, the design reflects how 4–6 year-olds learn best: by playing, touching, making, and seeing their own actions come alive.

Chapter 5
Field Observations & Findings

5.1. Observation Setup Overview

A series of field observations were conducted at a partner kindergarten located in Yokohama to examine how young children engaged with the conductive sponge-based interactive toolkit in an everyday learning environment. The workshop took place between 10:00 and 11:30 a.m., lasting approximately 90 minutes. It followed the children's regular English class, and participants appeared to be in a calm and attentive state.

A total of 24 children aged 4 to 6 participated, with four teachers present—two assigned to each age group (one lead teacher and one assistant). To maintain ecological validity and minimize observational interference, the activities were conducted as part of the children's regular schedule, without external observers in the room.

Participants were divided into two age-based groups:

- The 5-year-old group engaged first. Children were given the option to either use pre-cut conductive sponge pieces or create their own soft robot using sponge sheets and scissors. They explored both Mode1 (single-player touch-based interaction) and Mode2 (two-player collaborative play).
- The 4-year-old group followed. In this session, children used only pre-cut sponge shapes and participated in Mode1 and Mode2 activities in two rotation rounds.

Observations were conducted using a non-intrusive, naturalistic method. Researchers recorded children's interactions through photographs, field notes, and behavior logs, with teachers offering occasional support or prompts when necessary. These observations form the basis for the analysis of behavioral patterns, creative tendencies, and emotional engagement presented in the following sections.

5.2. Behavioral Interaction Analysis

Initial observations revealed that most children displayed immediate enthusiasm upon encountering the toolkit. Many reached for the sponge modules even before receiving full instructions, often commenting with surprise and excitement—“It jumping!” or “Can I try this?” These spontaneous reactions suggested that the toolkit’ s intuitive tactile interface effectively lowered the barrier to entry and invited exploration from the outset.

Figure 5.1 Children interacting with the toolkit during the workshop session.

Most children (N=24, aged 4 to 6) quickly understood the basic mechanism: pressing, squeezing, or connecting conductive sponge parts would trigger digital responses—such as animations, sounds, or character changes—on the screen. Compared to assembling pre-defined puzzles, higher levels of engagement were observed during activities that allowed children to cut, decorate, and personalize their own soft robots. In particular, one five-year-old girl cut a sponge into a cat shape, gave it the name "nene-chan," and shared a story about its adventures in space. This type of symbolic, narrative-rich interaction aligns with what Kaufman and Beghetto [30] describe as "Mini-C creativity"—personally meaningful creation that emerges from play.

Children's preferences for different feedback types also became apparent through both observational notes and teacher interviews (N=3, all full-time teachers at the host kindergarten). According to teachers, the most favored interaction was the "jumping character animation," followed by "stars or hearts appearing," and sound effects. These trends were also evident in field notes: one child repeatedly triggered the starfall animation and encouraged peers to watch, while another asked how to "make the astronaut appear" after observing a transformation in Mode1. In Mode2—designed for paired interaction—some children expressed surprise and laughter when the characters collided, triggering unexpected sound effects. These playful moments sparked social interaction, with questions like "Why did that happen?" or "Can we do it again?"

Repetitive play and exploratory behavior were commonly observed. Children often returned to their sponge creations to test different angles or pressure points, or to rebuild new robots from leftover materials. Notably, two children initiated a spontaneous "battle" scenario, each connecting their soft robot to a separate Arduino input and taking turns attacking and defending—demonstrating emergent cooperation, turn-taking, and creative role-play, all without adult instruction.

While most children preferred to work independently during the crafting stage, collaboration occasionally emerged once robots were completed. Some children complimented each other's designs—saying "I like yours" or "That looks cool"—and began discussing stories around their characters. One teacher noted that even children who were typically less engaged in craft activities seemed more animated during this session. Another teacher highlighted that since each group shared only one controller, children naturally had to wait their turns—an opportunity to practice patience and social awareness. This was also reflected in the teacher interviews, where one respondent noted: "Since the group had only one unit, it provided a chance for children to wait their turn."

A noticeable behavioral distinction appeared between those using pre-cut sponge templates and those allowed to freely design their own shapes. The pre-cut group generally focused on decorating or completing the "controller," whereas the free-cutting group showed greater ownership, often referring to their creations as "my robot" and showing stronger motivation to take them home. In fact, nearly all children chose to keep their controllers after the session, and several asked for extra sponge pieces to make more characters—an indicator of personal investment and emotional attachment.

These behavioral patterns illustrate the value of combining tangible interaction, immediate multisensory feedback, and creative autonomy in early childhood STEM learning. The toolkit not only facilitated intuitive hands-on engagement but also invited symbolic thinking, emotional investment, and collaborative storytelling. These findings provide strong empirical support for the research questions posed in this study. Specifically, they demonstrate how tangible materials and interaction design (RQ1) facilitated intuitive engagement; how multisensory feedback contributed to sustained attention and motivation (RQ2); and how opportunities for creative autonomy deepened children's emotional investment and personalized learning behaviors (RQ4).

5.3. Free Play vs. Task-Driven Activities

This section compares two contrasting modes of engagement observed across different workshop iterations: task-driven activities, as exemplified by the Zoo Workshop, and open-ended free play, as implemented in the final design workshop.

In the Zoo Workshop, children were guided to complete a tangible task—assembling animal-shaped conductive sponge parts to complete a circuit and light up an LED. While the initial reaction was enthusiastic, many children quickly lost interest once the LED was activated, signaling task completion. The structure offered clear cause-effect learning, but limited opportunities for creative expression or narrative continuation. Most children did not assign names to their creations or extend the interaction beyond the predefined goal.

In contrast, the final workshop emphasized free play, allowing children especially those aged 5 to cut their own sponge shapes, decorate them, and invent unique

Figure 5.2 Children are waiting for interacting with the toolkit.

characters. One child, for instance, created a cat-shaped soft robot, gave it a name, and verbally shared its story with a teacher and the researcher. These self-directed actions fostered a sense of ownership and emotional connection, leading to more sustained engagement and repeated interaction. Some children even invented new uses, such as connecting two controllers to simulate a battle game.

The findings suggest that while task-driven activities support foundational understanding of circuits, they may lack the narrative and imaginative depth that free play affords. Designing for early childhood should therefore strike a balance offering structured learning opportunities while preserving the space for personal expression, experimentation, and storytelling.

5.4. Naming, Narrative, and Collaboration

Observations revealed that opportunities for naming and storytelling emerged primarily during the free play phases, especially when children created their own soft robots. Children who used pre-cut sponge shapes often focused on placement and decoration, rarely extending their play into symbolic or narrative domains. In contrast, children who cut their own sponge designs were more likely to assign names, attributes, and backstories to their creations. One 5-year-old girl, for example, cut a sponge into a cat-like shape, named it "Neinei," (see Figure 5.3) and told a short story about its journey to space, involving interactions with other characters displayed on the screen.

Figure 5.3 Child designing a sponge character named "Neinei".

Additional examples also demonstrated children's expressive capabilities when provided with open-ended materials. One child, interested in marine animals, decided to create an octopus-shaped controller. He independently cut the sponge into a circular, tentacle-like form and used available stickers to add eyes and a mouth, later finishing the design with drawn-on details. Another girl proudly presented her bird-themed controller to teachers and classmates, decorating it with green craft paper and drawings to represent feathers and wings. These artifacts, shown in Figure 5.4, illustrate not only visual diversity but also children's ability to assign narrative functions and symbolic meaning to their creations.

These moments further support the argument that when children are given autonomy in shaping materials, they are more likely to transition from mere func-

Figure 5.4 Examples of child-designed characters: (Left) Octopus-shaped soft controller. (Right) Decorated bird character with story elements.

tional interaction to expressive storytelling and social sharing.

This pattern suggests that open-ended material design fosters Mini-C creativity [30], allowing children to imbue their creations with personal meaning. Ownership was frequently expressed through statements such as "This is mine" or "I made her," especially when the robot was self-designed.

Teachers played a subtle yet critical role in facilitating narrative expression. When educators asked prompting questions—"What is its name?" or "What can it do?"—children were more likely to elaborate on their characters and initiate storytelling. These forms of light scaffolding [6] appeared to activate social imagination and encourage shared play.

Although most children preferred to work individually during the crafting stage, post-creation interactions often led to spontaneous collaborations. Children showed their robots to peers, exchanged remarks, or even staged informal "battles" using Mode2 features. This progression—from solitary creation to shared storytelling—demonstrates how narrative expression and collaborative behavior can naturally emerge when autonomy and imagination are supported.

This section addresses RQ3, focusing on how children engage in naming, storytelling, and symbolic interaction when offered open-ended creation tools and multisensory feedback.

5.5. Role of Teachers and Emotional Reactions

Throughout the workshop, teachers played a non-directive yet supportive role that proved essential in fostering both emotional engagement and deeper narrative thinking. While children were largely allowed to explore the toolkit independently, teachers occasionally offered light scaffolding—posing questions like "What is this character's name?" or "What happens next?" These gentle prompts often sparked imaginative responses or encouraged children to engage in collaborative storytelling. In contrast, children who received no such guidance tended to treat the activity as a simple puzzle task, with fewer attempts at extending the interaction into a narrative experience.

Teacher feedback and observations revealed key patterns in emotional reactions. Several educators noted that children showed higher engagement when

Figure 5.5 Child collaborate together.

given autonomy to design and manipulate their own soft robots. Moments of visual or auditory feedback—such as an LED lighting up or a character jumping—frequently elicited joyful exclamations and prideful displays to peers or teachers. One teacher observed, "Even when just making the animation bounce, the children would repeat the action and laugh—it became part of their play."

Figure 5.6 Teacher with kids.

These reactions underline the emotional value of responsive interaction. Teachers reported that such multisensory feedback helped sustain attention and reinforced a sense of ownership and success. The presence of a familiar adult offering light encouragement created a safe environment for risk-taking, which in turn promoted deeper play and learning. This supports prior research emphasizing the importance of adult scaffolding in early creative and exploratory learning contexts. [6] [23]

5.6. Summary of Key Findings & Reflection

This chapter summarized key behavioral patterns and interaction insights observed during the final workshop. The toolkit was shown to be highly accessible—children quickly understood the interaction logic and responded positively to the intuitive, tactile nature of the conductive sponge materials. Activities that involved cutting, decorating, and crafting their own soft robots elicited deeper engagement and a sense of ownership. In contrast, puzzle-like tasks with predefined goals, while useful for initial comprehension, often lost their appeal once completed.

Multisensory feedback—such as visual animations and sound effects—proved particularly effective in sustaining children's attention and emotional excitement. Notably, children favored individual play during the creation phase, but organically transitioned to collaborative or performative play once their creations were complete, indicating that social interaction emerged as a secondary but meaningful layer of engagement. These findings address the central research questions by demonstrating how material affordances (RQ1), interaction design (RQ2), and feedback mechanisms (RQ4) collectively shaped the learning experience. While the toolkit succeeded in promoting creative exploration and emotional resonance, it also revealed areas for further refinement, such as designing more open-ended tasks with embedded narrative progression, and scaffolding peer collaboration without diminishing autonomy.

In the next chapter, these reflections will inform broader theoretical interpretations and guide future development directions.

Chapter 6
Discussion and Future Work

6.1. Revisiting Research Questions

This study was guided by four primary research questions, each of which aimed to examine the impact of material design, interaction style, teacher involvement, and multisensory feedback on children' s STEM engagement. The following section summarizes key findings in relation to each question.

RQ1: How do material affordances shape children's engagement with STEM concepts?

The use of soft, modular conductive sponge played a crucial role in facilitating intuitive engagement. Children aged 4–6 were able to easily press, cut, and assemble the sponge pieces without prior technical knowledge. Compared to rigid or screen-based tools, the softness and deformability of the sponge lowered the barrier to entry and encouraged spontaneous experimentation. This supports Piaget' s constructivist view that young children learn best through hands-on interaction and manipulation.

Observational and teacher feedback further affirmed this. Teachers noted that even children who typically did not enjoy making things (*"Children who usually do not engage much in hands-on activities"*) became immersed in crafting with the sponge. The material' s tactile nature, combined with its flexibility, created an inclusive platform for diverse learners, including those with lower motivation or attention.

Furthermore, based on observational insights, the toolkit proved effective in transforming what was originally a crafting-oriented activity into a learning experience with embedded STEM elements. Rather than replacing familiar forms of creative expression, the system extends them—offering children a playful yet educational bridge between hands-on making and foundational STEM logic. This hybrid approach not only retains the appeal of open-ended creation but also enriches the early childhood curriculum by introducing new learning pathways grounded in tangible interaction.

In particular, the softness of the conductive sponge proved beneficial not only for emotional safety but also for physical accessibility. For young children whose fine motor skills are still developing, the soft, squeezable material reduced resistance and fear of failure. Teachers noted that several 4-year-olds who typically hesitated with hard components showed increased willingness to engage with the sponge, pressing or rubbing it repeatedly to observe the outcome.

Moreover, when softness was combined with modularity—the ability to cut, recombine, and reshape components freely—it opened up a flexible creative space where children could explore at their own developmental pace. Four-year-olds, with teacher support, could cut and decorate basic shapes like animals or stars; five-year-olds were able to independently design characters or tools with functional roles in the game. This compositional freedom not only enhanced engagement but also promoted a sense of ownership and narrative thinking. In effect, softness provided the sensory safety, while modularity empowered self-expression.

This supported a hands-on cause-effect learning loop: children tested their inputs, observed feedback, and often verbalized discoveries (”It moves when I press here!”). The material's forgiving texture made trial and error feel safe, inviting even less-confident children to participate actively. This further demonstrates how tactile affordances—beyond abstract STEM content—can support foundational scientific thinking through sensory exploration and emotional engagement.

RQ2: What kinds of interaction designs best support creative play and learning?

The study compared structured tasks (e.g., completing a circuit-based puzzle) with open-ended creative play (e.g., designing a soft robot). Results indicated that children were more deeply engaged and emotionally invested when they had the freedom to cut, decorate, and personalize their own creations. In contrast, structured activities such as the “Zoo Workshop” often led to a sharp drop in interest once the task was completed.

This suggests that open-ended interaction better aligns with Vygotsky’ s Zone of Proximal Development (ZPD), where children’s potential is maximized through exploration rather than rigid instruction. Creative freedom allowed children to express symbolic meaning, invent stories, and exhibit what Kaufman and Beghetto [30] define as Mini-C creativity.

RQ3: What role do teachers play in supporting child-driven exploration?

Teachers played an essential but non-directive role in facilitating the learning environment. Through subtle scaffolding—such as asking questions like *“What’ s its name?”* or *“What is it doing?”*—teachers encouraged children to extend their interaction into narrative play. These gentle prompts often sparked imaginative responses that would not have emerged through tool use alone.

For instance, in one observed moment, a child repeatedly pressed the conductive sponge, triggering a jumping animation on screen. A teacher nearby asked, *“Did your animal jump? Where is it going?”* The child paused and replied, *“He’s flying to space! I pressed it, so he jumps!”* This exchange illustrates how adult questioning supported both symbolic thinking and a clearer cause-effect understanding of their interaction. By linking physical input to story-driven output, the teacher scaffolded the child’ s transition from reactive manipulation to intentional narrative construction.

In contrast, when no adult guidance was provided, some children treated the toolkit primarily as a mechanical device—pressing to trigger a reaction—without verbalizing or assigning symbolic meaning. This contrast highlights the importance of teacher facilitation in helping children move from basic sensorimotor engagement toward deeper conceptual or imaginative learning.

These findings suggest that while the toolkit’ s tactile design encourages spontaneous play, it is often the adult’ s role that unlocks the full narrative and educational potential. As such, the TaleTouch system benefits most when used in environments where caregivers or educators can sensitively scaffold exploration without taking control.

RQ4: How can tangible-digital feedback enhance children's narrative engagement?

The integration of sound, light, and animation significantly enhanced emotional response and sustained attention. Children were particularly drawn to visual effects such as falling stars and jumping characters. *Mode1*, which provided instant feedback to individual actions, led to repeated experimentation. *Mode2*, which required collaborative input, promoted laughter and social bonding, especially when sound effects were triggered during collisions.

Teachers observed that different feedback types influenced different emotional reactions—for instance, children were more vocal and joyful when the system responded with sound or sparkle animations. These findings validate the importance of multi-sensory feedback in sustaining interest, promoting re-engagement, and supporting symbolic play.

6.2. Design Insights & Toolkit Uniqueness

This section synthesizes key design insights derived from the iterative development and classroom implementation of the conductive sponge-based toolkit. It outlines the unique qualities that distinguish the toolkit from existing early STEM educational tools, focusing on teacher usability, material affordances, interactive structure, and expressive potential.

A. Teacher-Scaffoldable System

One of the notable strengths of the toolkit is its ability to be naturally embedded into existing classroom routines without requiring extensive teacher training. Teachers were able to understand and guide children through the activity structure with ease, often treating it as an extension of creative play rather than a separate instructional tool. Feedback from participating educators indicated a willingness to continue using such tools in the future, as it *"feels like play, but naturally leads to learning."*

Compared to conventional STEM kits that often require specific training or technical knowledge, this system significantly reduces implementation barriers. Teachers served as light scaffolds—asking guiding questions, encouraging reflection, and helping children extend their exploration—without dominating the learning experience.

B. Material Innovation: Soft, Safe, and Modular

The use of soft conductive sponge as the primary interactive medium introduced several unique advantages. The material is safe to handle, easy to cut, and invites tactile engagement, making it ideal for preschool-aged children who may lack refined motor skills. Unlike rigid components in systems such as *Micro:bit*, the sponge' s deformability lowers cognitive and physical entry thresholds.

To the best of our knowledge, this is the first application of conductive sponge in a tangible user interface (TUI) system designed specifically for early childhood learning. Its softness not only supports physical manipulation but also encourages children to create characters and shapes with emotional and symbolic meaning—bridging craft-based expression and STEM interaction.

C. Hybrid Tangible-Digital Feedback

The toolkit' s hybrid feedback system connects tangible input (squeezing, assembling, or pressing sponge pieces) with digital output (visual and auditory responses on screen). This coupling reinforces cause-effect understanding while sustaining emotional engagement through stimuli such as falling stars, animated characters, and playful sounds.

By linking physical action with digital consequence, the system supports both logical learning and imaginative immersion. Children quickly developed mental models of how their actions triggered feedback, leading to repeated interaction and verbalized expressions of discovery (*"Look! It jumps when I press it!"*). This structure aligns with multimodal learning principles and helps scaffold both technical and narrative understanding. Furthermore, because the toolkit's design relies on physical interaction rather than verbal instruction, it places minimal demands on language skills. Aside from brief teacher prompts, the entire experience is largely language-independent, allowing children to engage through exploration and action. This absence of language barriers appeared to enhance their expressive behaviors and sustained interest, making the interaction feel inclusive and intuitive.

D. Platform for Expressive, Symbolic Play

Beyond structured tasks, the toolkit functioned as an open-ended platform for expressive exploration. Children were free to name their creations, invent characters, and tell stories—often without adult prompting. This autonomy fostered what Kaufman and Beghetto [30] describe as *Mini-C creativity*: personally meaningful expressions that emerge in early stages of learning.

Teacher feedback supported this observation. One noted, *"The act of shaping and storytelling became a source of motivation for the children."* Another reflected that children developed a strong sense of ownership: *"They said, 'This is my creation,' and began to treat it with personal meaning."*

By integrating crafting, sensory feedback, and character-based interaction, the toolkit empowered children to not only understand simple STEM concepts, but also to emotionally invest in the learning process—an essential element for sustained engagement in early childhood education.

6.3. Conclusion, Limitations, and Future Work

A tactile, modular toolkit made from conductive sponge was developed and evaluated in this study to encourage early STEM involvement in children aged 4 to 6. Through the use of developmentally appropriate actions, hands-on crafting, modular study, and multisensory digital feedback, the toolkit allowed children to engage with abstract STEM concepts in a natural and intuitive way.

Workshop results showed that the toolkit successfully promoted self-directed exploration, emotional involvement, and symbolic expression. In addition to learning about circuits and cause-and-effect interactions, children also demonstrated narrative thinking by giving their creations names, telling stories, and sharing them with their peers through both structured puzzle-based assignments and open-ended creation activities. The soft and flexible materials encouraged inclusive participation, especially among children who struggled with fine motor skills or had difficulty communicating verbally.

Limitations and Future Work

Lack of Longitudinal Data. While short-term engagement was strong, the long-term effects on knowledge retention and STEM concept internalization remain unknown. Future studies should conduct longitudinal investigations to better understand sustained learning outcomes.

Task-Play Balance. While structured activities helped convey logical ideas, they sometimes constrained creativity. Conversely, fully open-ended sessions lacked scaffolding for some learners. Future iterations could adopt hybrid approaches that embed goal-oriented tasks within narrative-driven play to balance educational value with playful exploration.

Limited Cooperative Play. Although spontaneous teamwork emerged, most interactions remained dyadic. Future designs could incorporate more explicit co-play mechanisms—such as shared goals, synchronized triggers, or multi-user feedback systems—to promote social learning and peer collaboration.

Age-Appropriate Feedback Tuning. The current audiovisual feedback was tuned for 4-5-year-olds. To support a broader age range, future versions could explore scalable feedback, including variable animation speeds, more nuanced sound responses, or adaptive interactivity for older children with diverse attention spans.

Multisensory Feedback Enhancement. The present system focuses on visual and auditory feedback. Future versions could explore incorporating tactile modalities, such as gentle vibrations delivered through wearable bands or embedded motors in the sponge controller. These haptic cues may enhance immersion, reinforce cause-effect learning, and support children with auditory sensitivities or attention regulation difficulties.

Contextual Generalizability. Testing was limited to a single Japanese kindergarten. Broader trials across multiple settings—including informal learning spaces, diverse cultural environments, and teacher-scarce contexts—are essential for evaluating the toolkit's generalizability and robustness.

Material Safety for Young Participants. For use in less supervised or mixed-age environments, enhanced safety measures are needed. Future designs may apply bitter-tasting coatings to sponge parts to deter mouthing behavior while preserving the soft tactile interaction that defines the toolkit's appeal.

Adapting for Age and Cultural Diversity. To accommodate developmental differences, larger, easier-to-grasp components and simplified feedback (e.g., brighter lights, slower motion) may benefit toddlers aged 2-3 under adult supervision. Conversely, older children could explore additional programmable modules (e.g., logic blocks or sensor triggers) to extend STEM depth. A language-free visual instruction guide—using culturally neutral illustrations and step-by-step pictograms—is also under development to enhance accessibility in multilingual or low-literacy settings.

Future Development Focus. Based on these directions, future iterations will focus on: (1) expanding storytelling elements via new characters and animations (2) developing teacher-facing versions with integrated lesson guides (3) supporting broader age groups through modular scalability and programmable add-ons (4) improving multisensory feedback and instruction design for inclusive, international contexts.

Finally, by proposing a low-threshold, high-engagement tactile interface that fosters children's creative independence, emotional expression, and collaborative imagination—alongside conceptual learning—this work contributes to advancing the field of early STEM education. This aligns with earlier discussions on material affordances (see 6.1), where softness and flexibility encouraged initial engagement, and demonstrates how differentiated scaffolding—not hardware complexity—is key to developmental adaptability.

6.4. Final Conclusion and Reflection

This research began with a simple but powerful question: how can young children engage with STEM in ways that are playful, creative, and developmentally appropriate? Through multiple design iterations and real-world workshops, a tangible-digital toolkit was developed that combines low-barrier tactile interaction with immediate feedback, emotional resonance, and space for narrative imagination.

The toolkit' s unique design blends playfulness, educational value, and creative freedom, filling a critical gap in early STEM learning. By allowing children to press, build, cut, and imagine, it supported not only logical thinking but also symbolic play and emotional expression. Observations showed that even children with limited prior experience could confidently explore, invent stories, and engage others—demonstrating both cognitive and emotional growth.

From a design researcher's perspective, this project became more than an educational intervention; it became a journey of listening and learning from children. Rather than just delivering a product, the process involved co-creating experiences—guided gently by teachers, shaped by feedback, and brought to life by the children themselves.

6.4.1 Reflection as a Researcher

Over the past two years, through conducting workshops with children, I've come to deeply feel the incredible potential each child holds. Watching them create with their own hands—immersed in the moment, eyes sparkling with joy—was truly inspiring. I try my best to remember each of their cute, handmade creations. When they encountered something unfamiliar, many of them asked questions with such curiosity and enthusiasm. Sometimes, they even asked things I hadn't prepared for—questions that made me pause and think. These unexpected moments reminded me how fresh and insightful children's perspectives can be, and how much I've learned from being with them.

These experiences also taught me how emotionally expressive children can be. I remember moments when they were sad that the workshop was ending—some even asked their teachers, "Does this big sister really have to leave?" Hearing such honest and heartfelt words in unexpected moments often caught me off guard. Just a second ago, I might have been preoccupied with the research design, but suddenly I was reminded—what I'm doing truly matters. Children's emotions are genuine and direct: when they're happy, they show it wholeheartedly; if they get upset, it's just a fleeting reaction. There were many moments when their energy and presence inspired me to keep going. From the crowded sign-up slots at the Shiodome workshops to the heartfelt feedback from the children who participated, I realized that what I had initially hoped for—just to spark some interest in STEM—had grown into something far more meaningful. The children's joy, their smiles, the way they held my hand and spoke to me with such warmth…I’ m deeply grateful to all the children, parents, and educators who took part in these workshops. I would also like to express my sincere appreciation to the teachers at Greenport Nursery in Sakuragicho, Yokohama. They provided thoughtful and detailed feedback about the children’s habits and behaviors—even in the early planning stages. Their insights gave me perspectives I could never have discovered on my own as a developer, and ultimately helped shape the toolkit into something more effective and meaningful.

This project has reminded me that I am indeed working on something truly meaningful. More than anything, I hope that the children grow up in an environment where they can learn and express themselves freely. Whether girls or boys, I want them to keep being brave and pursue what they truly want to do. I believe that early STEM education can spark curiosity and confidence in all children—girls can become engineers, and boys can pursue creative paths too. What matters most is that every child feels empowered to explore and grow in their own way.

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